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THE DESIGN, TEST AND EVALUATION OF A MINIATURIZED ELECTRIC FIELD METER

J. E. Evans

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Interim Technical Report #13

Contract DA-31-124-ARO-D-246

U. S. Army Research Office - Durham
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Details of illustrations in this document may be better studied on microfiche.

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FOREWORD

The work reported herein was sponsored by the United States Army Research Office, Durham, under Contract No. DA-31-124-ARO-D-246. The study presented herein was conducted by Mr. James E. Evans in fulfilling the requirements for a thesis in his Master of Science program at The Ohio State University.

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The principle of operation of a field mill is explained and an analytical analysis of the fixed conductor field mill is presented. Several previous field mill designs are reviewed, and the summary presents the different field mill designs in tabular form. A fixed conductor field mill is designed to operate in a subsonic wind tunnel whose airstream contains a particulate suspension. Various field mill vane configurations are designed, calibrated, and evaluated with the configuration best suited to the environment used to obtain measurements of the magnitude and polarity of the electric field in the wind tunnel.

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IV - NOMENCLATURE

A	maximum exposed area of the stator
a	instantaneous exposed area of the stator
C	Capacitance
$\bar{D}$	electric flux density, a vector
$\bar{E}$	electric field strength, a vector
I	peak-to-peak current
i	time varying current
Q	net charge
R	resistance
t	time
t_p	half period of the exposure-screening cycle
V	peak-to-peak voltage
v	time varying voltage
w	angular velocity of the exposure-screening cycle
z	impedance
ϵ	permititivity or dialectric constant
ρ_s	surface charge

V INTRODUCTION

In the course of an investigation of electrostatic phenomena associated with a vortex seeded with a particulate suspension (ref. 3), it was necessary to obtain measurements of the variation of the electric field through a vortex. In order to accomplish the above a small, aerodynamically shaped, mechanical collector was needed.

The primary objective of this investigation was to design, test and evaluate such a collector, or field meter, which is commonly referred to as a "field mill".

A secondary objective was to summarize and organize the work of previous investigators in the development of field meters.

VI PRINCIPLE OF OPERATION OF THE FIELD MILL

In figure 1 a field mill has been shown schematically as three plates: a grounded plate, a conductor, or stator, plate above the grounded plate connected to the grounded plate by a resistor, and a grounded screening plate above the stator which moves from left to right.

A negatively charged body is now placed above the field mill plates, thus creating an electric field of strength $\bar{E}$ between the body and the plates. As a result of this electric field an electric flux density, $\bar{D}$, is also present. The flux density can be defined as:

$$\bar{D} = \epsilon \bar{E} \qquad (1)$$

where:

ϵ = permittivity

$\bar{D}$ indicates a surface charge density and is a vector in the same direction as $\bar{E}$.

The field mill plates are all electrical conductors. A conductor may be defined as a medium in which the electric field is always zero. That is, when a conductor is brought into an electric field, the electrons in the conductor flow until a surface charge distribution is built up that reduces the total field in the conductor to zero. The surface charge distribution is said to consist of "induced charges". Since the electric flux density is proportional to $\bar{E}$, it is also zero in a conductor.

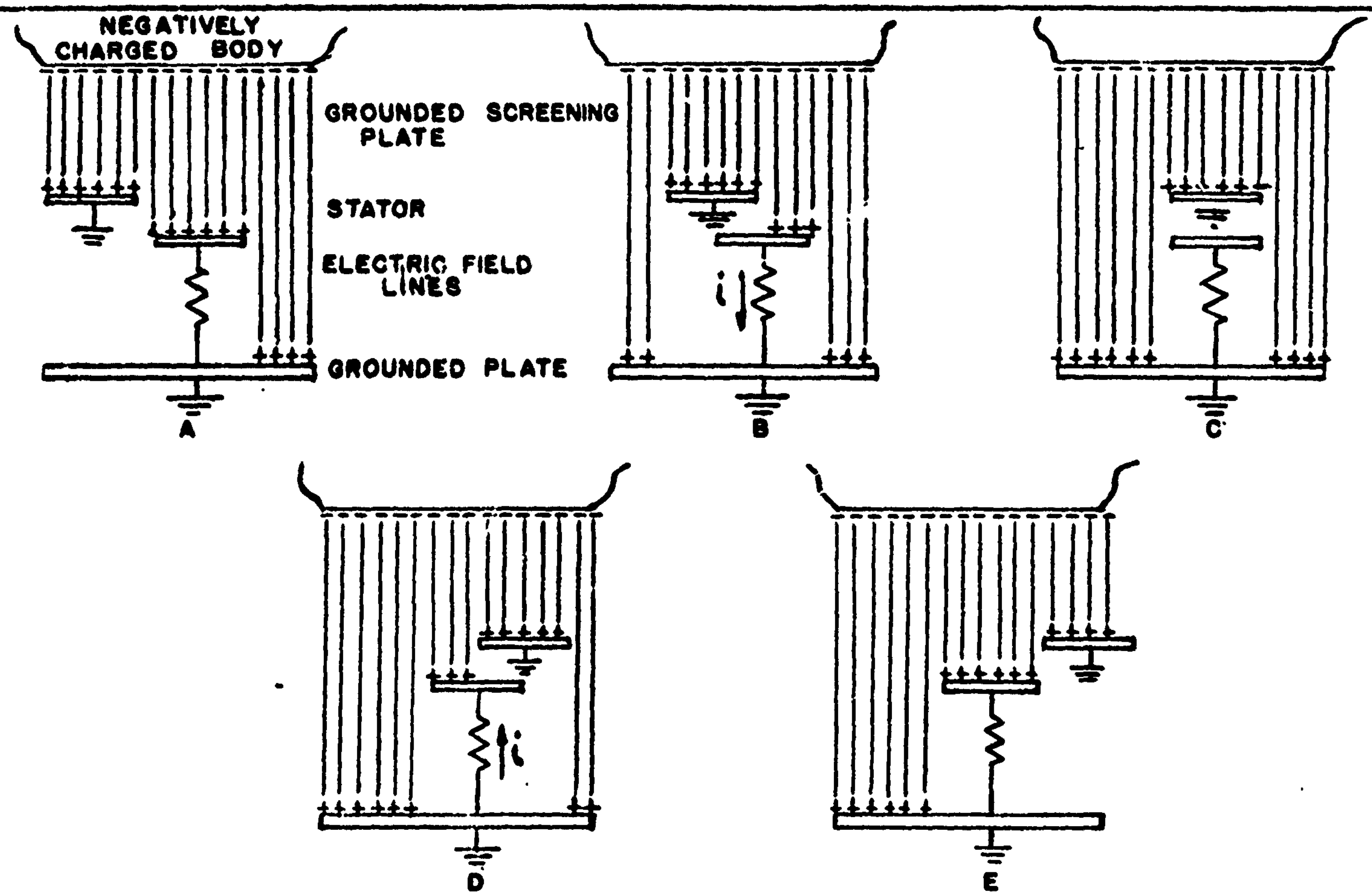


FIGURE 1 – PRINCIPLE OF OPERATION OF A FIELD MILL (REF. 12)

With the above preliminary observations, one can now determine the magnitude of the induced charges on the field mill plates. Figure 2 presents a differential volume half in a plate and half in the air.

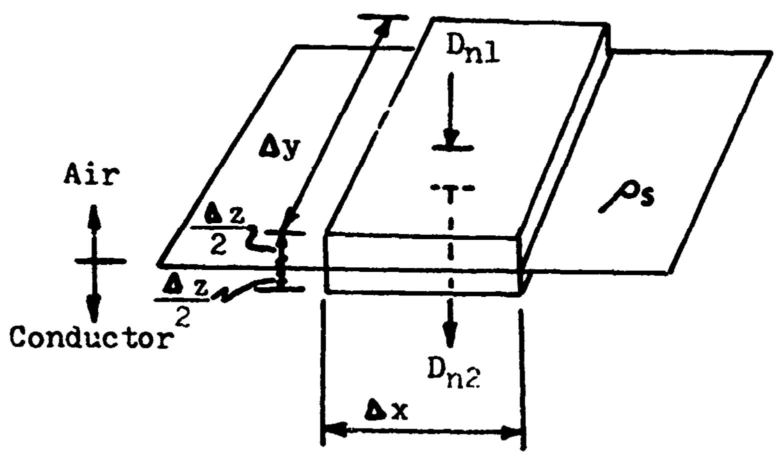


Figure 2 (ref.10)

where

D_{n1} = average inward normal electric flux density in air

D_{n2} = average outward normal electric flux density in the conductor

ρ_s = surface charge on the plate

Gauss's law for an electric field, (ref. 10) states:

"The surface integral of the normal component of the electric flux density $\overline{D}$ over any closed surface equals the charge enclosed."

Thus in symbols

$$\iint \overline{D} \cdot d\overline{s} = Q \qquad (2)$$

where Q is the net charge.

Now, if one lets $\Delta Z \rightarrow 0$ to eliminate the surface area of the ends of the volume element, the total flux over the element is entirely due to the normal fluxes.

By applying Gauss's law to the volume element with the above condition, the integral reduces to

$$D_{n2} \Delta x \Delta y - D_{n1} \Delta x \Delta y = Q = \rho_s \Delta x \Delta y$$

Dividing by the area $\Delta x \Delta y$

$$D_{n2} - D_{n1} = \rho_s$$

But D_{n2}, is the electric flux density in the conductor which is zero. Therefore

$$- D_{n1} = \rho_s \qquad (3)$$

That is the electric field induces a surface charge on the conductor equal in magnitude to the normal component of the electric flux density and opposite in sign.

Using the above basic principles the operation of the field mill has been illustrated in figure 1 A - E. When the stator is not shielded (figure 1A) by the screening plate the negatively charged body induces a charge of opposite sign on the stator surface. As the grounded screening plate shields part of the stator from the electric field lines (figure 1B) the surface charge on the shielded portion of the stator plate must go to zero. Therefore charge flows to ground through the resistor. When the stator is completely shielded (figure 1C) all bound surface charge on it must go to zero and flow through the resistor to ground. As the screening plate moves away from the stator and re-exposes part of the stator surface to the electric field lines (figure 1D) induced surface charge must reappear on that exposed area of the stator. Hence charge flows from the ground through the resistor to the stator surface. Finally, the stator is completely exposed to the electric field (figure 1E) and all the original surface charge re-appears on the stator plate.

Thus, if the stator is alternately exposed to and screened from an electric field, an alternating current will be induced whose maximum amplitude will be proportional to the surface charge density and thus to the electric field strength, $\bar{E}$.

VII THEORETICAL ANALYSIS OF THE FIXED CONDUCTOR FIELD MILL WITH ROTATING SCREENING PLATE

The fixed conductor field mill can be analyzed as one plate of a capacitor with the other plate being a charged body a fixed distance away, as shown in figure 3,

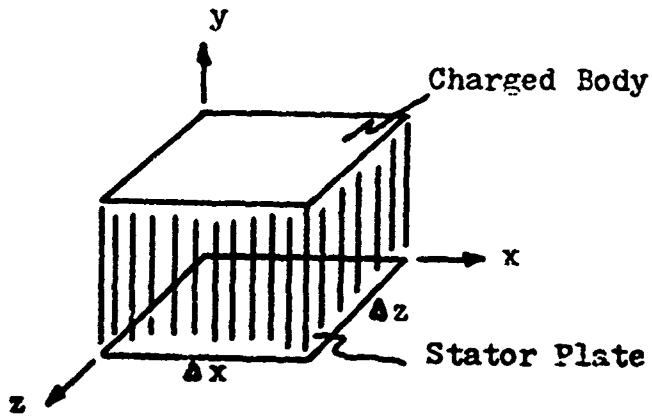


Figure 3

with the assumption that the distance between the stator and rotating screening plate is much smaller than the distance between the stator and charged body. From Chapter II, equation 3 the surface charge on the differential area $\Delta x \; \Delta z$ is

$$\rho_s = D_z = \frac{\Delta Q}{\Delta x \Delta z}$$

where ΔQ is the net charge on the stator area $\Delta x \; \Delta z$. Also, the definition of electric flux density was

$$D_z = \epsilon E_z$$

equating the two expressions for D_z one obtains

$$Q = \epsilon E_z \Delta x \Delta z \qquad (4)$$

Integrating the above equation with the assumption that E_z and ϵ are constant with respect to time and space results in

$$Q = \int_0^Q \Delta Q = \epsilon E_z \iint dx\, dy = \epsilon E_z a$$

or

$$Q = \epsilon E_z a \qquad (5)$$

where "a" is the instantaneous exposure area at time t.

Using equation 5 for the net charge induced on an area "a", W. W. Mapleson and W. S. Whitlock (ref. 12) have analyzed the alternating current and voltage output signal of a field mill for two different time varying wave forms of the instantaneous area "a". They let the stator have a capacity C, a resistance R to ground, and defined the following parameters

A = the maximum exposed area

w = angular velocity of the exposure-screening cycle

t = time

Then they modelled the following two cases.

Case I.

If one lets "a" vary sinusoidally, the following equation holds

$$a = A/2\ (1 + \sin wt)$$

from equation 5 the charge is given by

$$Q = \frac{\epsilon E_z A}{2}\ (1 + \sin wt)$$

but the current is defined to be

$$i = \frac{dQ}{dt} \qquad (6)$$

Therefore

$$i = \frac{d}{dt}\left(\frac{\epsilon E_z A}{2}\ (1 + \sin wt)\right)$$

Differentiating

$$i = \frac{\epsilon E_z Aw \cos wt}{2} \qquad (7)$$

with the peak value of current being

$$I = \frac{\epsilon E_z Aw}{2} \qquad (8)$$

The voltage across the C and R of the stator is given by

$$v = iz = \frac{\epsilon E_z Aw}{2}\ z \cos wt \qquad (9)$$

where z, the impedance of R and C in parallel, is given by

$$z = R/(w^2C^2R^2+1)^{\frac{1}{2}}$$

Substituting the value of z into equation 9 one obtains

$$v = \frac{\epsilon E_z AwR}{2(w^2C^2R^2+1)^{\frac{1}{2}}} \cos wt \qquad (10)$$

If $w^2C^2R^2 \gg 1$, then equation 10 reduces to

$$v = \frac{\epsilon E A}{2C} \cos wt \qquad (11)$$

and the peak voltage V is given by

$$V = \frac{\epsilon A E_z}{2C} \qquad (12)$$

Case II

If one lets "a" have a triangular wave form, and considering only a half-cycle at the end of which the stator is fully exposed, the instantaneous area is given by

$$a = At/tp$$

where tp equals π/w, the half period of the exposure-screening cycle. From equation 5 the induced charge on this area is

$$Q = Q_0 + \frac{\epsilon E_z A}{\pi} wt$$

where Q_o is the charge on the stator at the start of the half cycle. The current from equation 6 would be

$$I = \frac{dQ}{dt} = \frac{\epsilon E_z A w}{\pi} \qquad (13)$$

If v is the instantaneous voltage across C and R, then

$$\frac{dv}{dt} = \frac{1}{C}\left(i - \frac{v}{R}\right) \qquad (14)$$

Integrating equation 14 with the following boundary conditions:

B.C. 1 $t = o$, $v = Q_o/C$

B.C. 2 $t = \pi/w$, $v = V$

and substituting for i results in

$$V = \frac{\epsilon EAwR}{\pi} \left(1-\exp\left(-\pi/wCR\right)\right) + \frac{Q_o}{C} \exp\left(-\pi/wCR\right)$$

But in the steady state the voltage at the end of the half cycle must be equal and opposite to the voltage at the beginning, or $Q_o/C = -V$. Hence

$$V = \frac{\epsilon EAwR \left(1- \exp\left(-\pi/wCR\right)\right)}{\pi \left(1 + \exp\left(-\pi/wCR\right)\right)} \qquad (15)$$

Expanding $\exp\left(-\pi/wCR\right)$ as a series, equation 15 reduces to

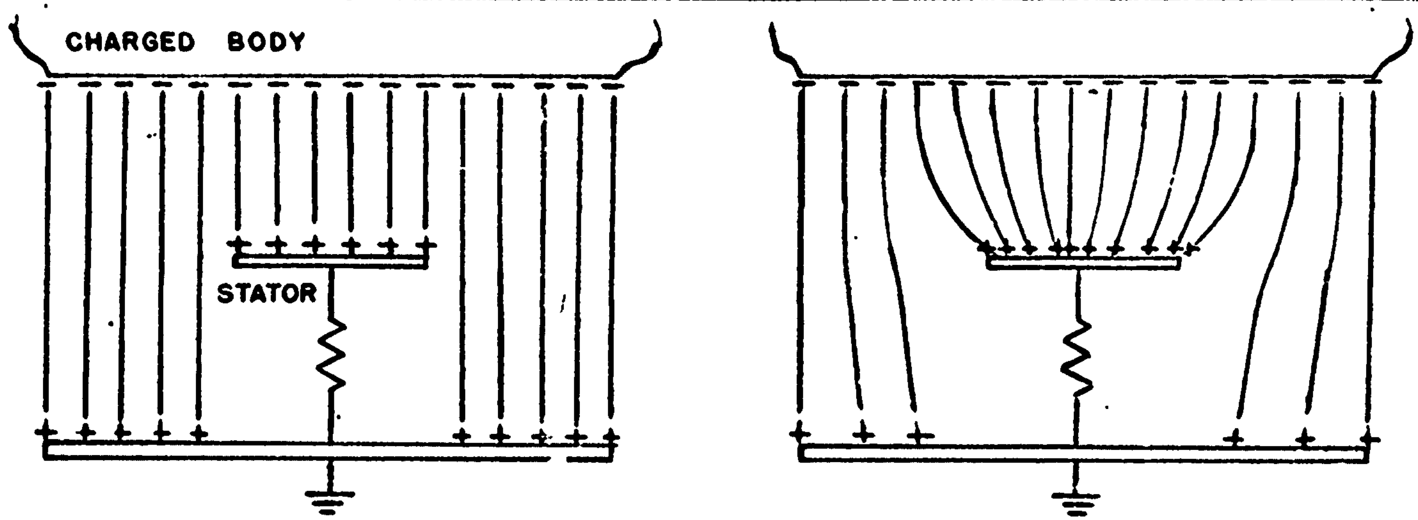
$$V = \frac{\epsilon EA}{2C} \left(1 - \frac{\pi^2}{12w^2C^2R^2} + \text{higher powers}\right)$$

Again, if $w^2C^2R^2 \gg 1$, the equation simplifies to equation 12

$$V = \frac{\epsilon EA}{2C}$$

Therefore both cases predict that the output peak voltage V of the field mill will be directly proportional to the electric-field strength and independent of w, the angular rotation of the screening-cycle, if the condition that $w^2C^2R^2 \gg 1$ is satisfied.

Equation 12 seems like a very simple theoretical equation. But it is very difficult to employ because the maximum exposure area A, of the field mill is difficult to predict due to electric field fringing effects. Figure 4A shows the ideal equally spaced electric field lines terminating perpendicularly on the stator surface. Figure 4B shows how the fringing of the electric field, as is the true situation, increases the number of lines terminating on the stator. This increase in field lines has the effect of making the equivalent maximum exposure area in the ideal situation much larger than the physical maximum exposure area of the field mill. For this reason equation 12 can be used only to isolate the design parameters of importance and experimental means must be used to obtain the exact relationship between the electric field strength and the field mill output voltage.



A- IDEAL ELECTRIC FIELD LINES

B- REAL ELECTRIC FIELD LINES

FIGURE 4 - ELECTRIC FIELD FRINGING EFFECTS ON STATOR EXPOSURE AREA

VIII REVIEW OF PREVIOUS INSTRUMENTS

A Cylindrical Field Mill

According to Mapleson and Whitlock (ref. 12), the first field mill was described by the German Matthias in 1926. It consisted of two semi-cylinders, electrically insulated from each other but mechanically joined, which were rotated in the presence of an electric field. The charges induced on the semi-cylinders resulted in a sine-wave current. This current was amplified and used to measure the electric field.

Kirkpatrick and Miyake (ref. 9) and Gunn (ref. 5) further developed the cylindrical mill, independently, in 1932. Kirkpatrick and Miyake transformed the electric field measuring device into a voltmeter as shown in figure 5A, by placing the rotating cylindrical conductors a fixed distance away from two spherical electrodes which were connected to the potential to be measured. Hence, the electric field between the electrodes depended only on the potential across them and the device could be calibrated accordingly.

Gunn also transformed the field mill into a voltmeter, or electrometer, by essentially the same method as Kirkpatrick except that his electrodes were two semi-cylinders, as shown in figure 5B.

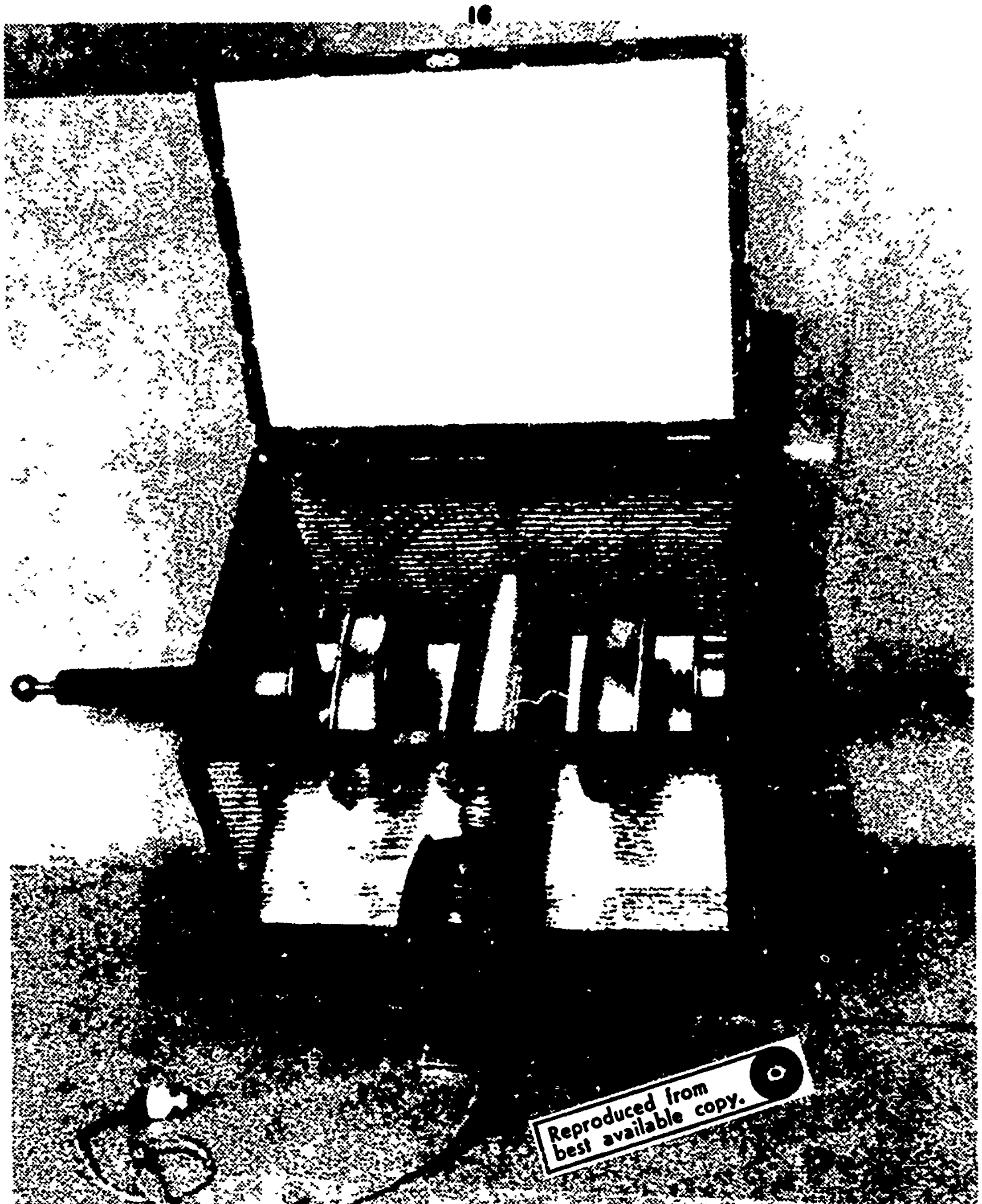


FIGURE 5A - KIRKPATRICK & MIYAKE VOLTMETER, 1932

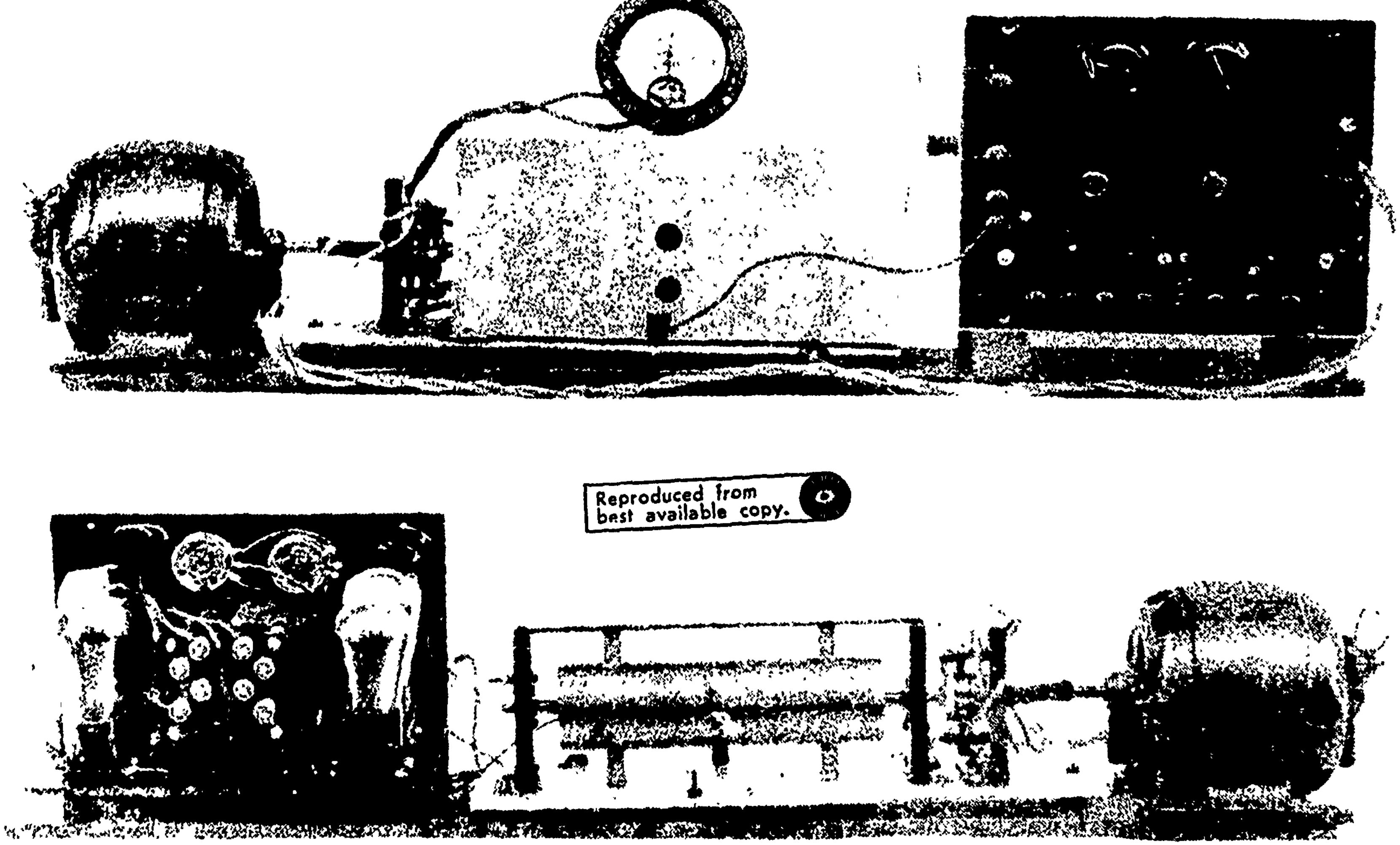


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FIGURE 5B – GUNN'S ELECTROMETER, 1932

Both Gunn and Kirkpatrick added a commutator to their instruments which determined the sign of the applied potential (or charge). Figure 6 shows Gunn's voltmeter, or electrometer, schematically in order that this method of polarity determination can be examined. If one studies Gunn's electrometer, it is observed that the steady potential on the semi-cylinder electrode, 4, (which is highly insulated by amber) is converted to an alternating potential by the rotating conductors 6 and 7 (field mill). Then the resulting alternating current is amplified by an array of vacuum tubes 8 and 9. Instead of measuring the resulting a.c. potential directly, it is passed through a commutator, 3, which is operating in strict synchoronism with the rotating conductors. This rectifies the output a.c. and it is passed to a direct current indicator, 18. Now a reversal in sign of the applied potential will reverse the phase of the a.c. and the direct current indicator will reverse sign.

In 1935 Henderson, Goss and Rose (ref. 7) used a voltmeter exactly like Kirkpatrick's for voltage measurements up to 830 kilovolts. And in 1937 Thomas (ref. 15) used the Kirkpatrick instrument immersed in oil which increased the dielectric constant of the system to such an extent that no amplification of the alternating current was necessary for high voltage applications.

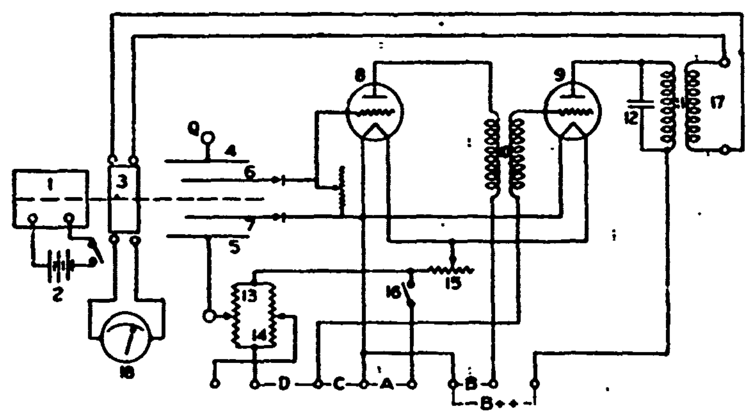

FIGURE 6- SCHEMATIC OF GUNN'S ELECTROMETER

B - Fixed Conductor Field Mill

While Matthias, Kirkpatrick, et. al. were developing the rotating conductor field mill, Macky in 1933 (ref. 11) built an instrument utilizing a fixed conductor which was alternately covered and uncovered by a rotating vane thus generating an alternating current. This instrument worked satisfactorily in electric field strengths of 1000 volts per meter.

In 1935 Macky (ref. 11) built another similar field mill, figure 7, for measuring electric fields on the order of 0 to ± 400 volts per meter. In this instrument the fixed conductor, or stator, was made of alternate quadrants of a circle which were grounded through a high impedance. Directly above the stator was a rotating grounded vane identical in shape to the stator thereby alternately screening and exposing the stator from the electric field. The resulting alternating voltage signal was approximately of triangular wave-form. The signal was then amplified and automatically recorded. The polarity of the electric field was inherently determined by the signal amplifier.

Harnwell and Van Voorhis, (ref.6) were also developing a field mill at approximately the same time, 1935 as Macky. Their instrument was built to operate as a null type meter using a three vane configuration as shown in figure 8. The stator, vane A, was a full disk, and above this disk were

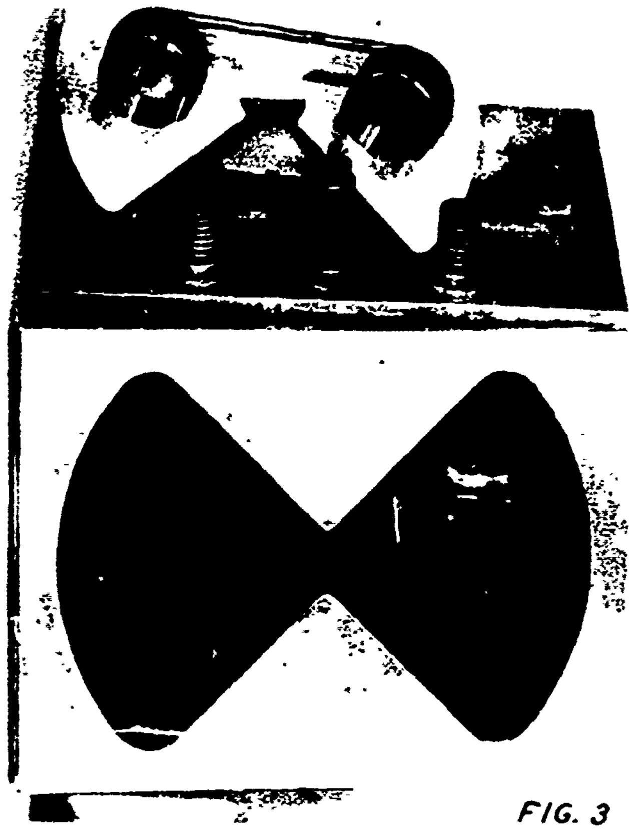

FIG. 3

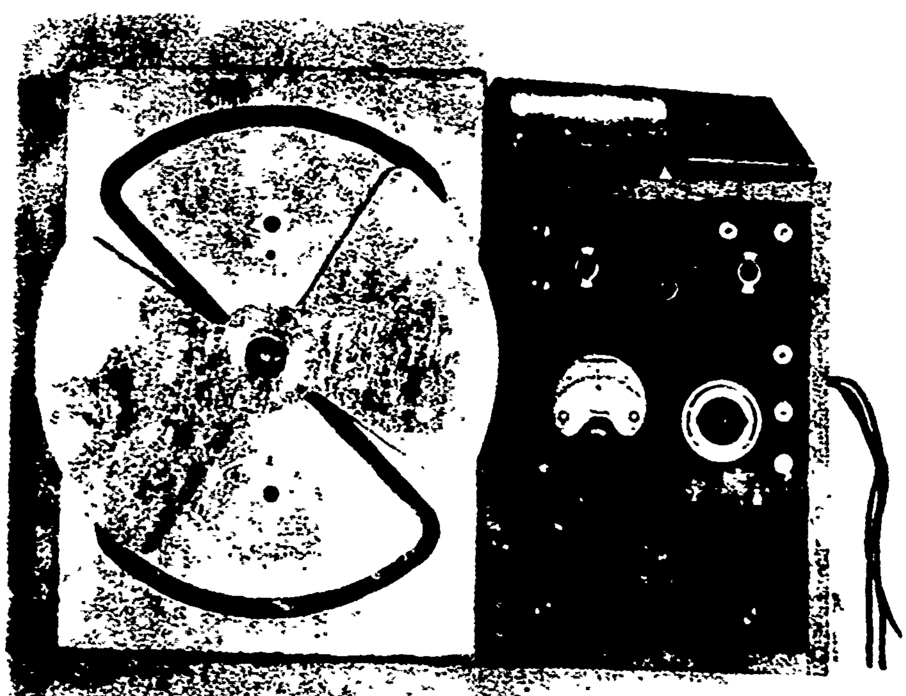

FIG. 4

FIGURE 7– W. A. MACKY'S FIELD MILL, 1935

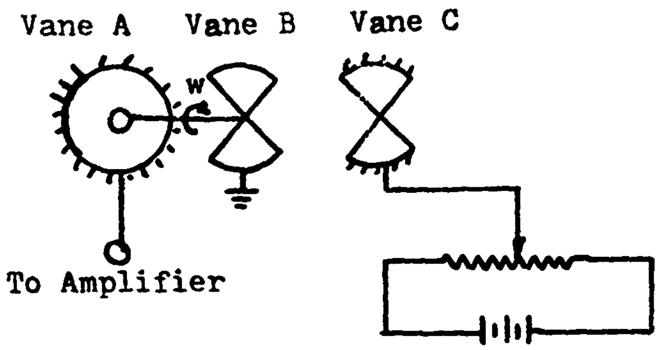

Figure 8

vanes B and C, again made of alternate quadrants of a circle. Vane B was used as a grounded rotor and vane C was held fixed. Now, if vane C was grounded, the rotor would alternately shield and expose that area of the disk not screened by vane C to the electric field to be measured and operate exactly like Macky's. However, Harnwell and Van Voorhis connected vane C to a power supply and adjusted the potential to create a field under this vane equal to the unknown electric field and of the same polarity as the unknown electric field. Under these conditions the alternating signal was reduced to zero. Hence, the electric field strength was measured by the amount of potential needed to null the instrument and the polarity of the null voltage was the polarity of the electric field.

C - Variations of the Field Mill From 1932 to 1971

The two designs of the field mill, as presented by Matthias and Macky, proved very popular and many variations of these instruments have been developed between 1933 and 1971. However, the fixed conductor design has proved the most popular since it eliminates the commutator noise source. The basic variations in the field mill have been the type of conductor used, fixed or rotating (as described previously), the alternating signal wave form, the method of determining polarity of the applied field, the design of the signal amplifiers, and the ability of the instruments to respond to nonsteady fields. A discussion of these variations follows with a partial list of the early instruments using them.

The alternating signal has been of two wave forms, triangular - Macky (1937), Trump 1940), Smith (1954), et. al., and sinusoidal - Matthias (1926), Kirkpatrick 1933), Gunn (1932), Van Atta (1936), et. al. The shape of the stator and rotor, as shown in figure 9, determine which of these wave-forms will result.

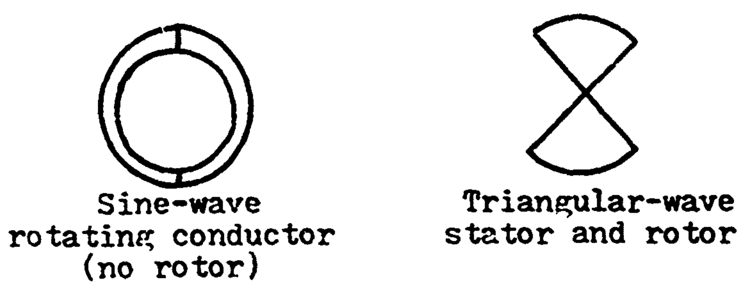

Figure 9

The methods of determining polarity of the measured electric field have been numerous. Some of the early instruments rectified the current by a commutator - Kirkpatrick, Gunn, Waddel (1948), et. al. An auxiliary synchronous generator has been added and either used in conjunction with phase - sensitive detectors or added directly to the signal to displace the zero of the instrument - Mapleson and Whitlock (1954), et. al. While a very simple method of polarity recognition was introducing an asymmetry in the wave form and displaying it on an oscilloscope - Lueders (1943), et. al. (see appendix 1 for detailed description).

The method of amplifying the alternating current while maintaining a high input impedance has progressed with the development of electronics from vacuum tube amplifiers to solid state integrated circuits.

The majority of the field mills were designed to measure steady electric fields. Consequently, they had a very slow response time. But Luders, 1943, (ref. 12) designed a field mill employing a circular stator with a fixed perforated grounded plate over it and then rotated a similar perforated grounded plate between the two. He thus obtained very rapid response by greatly increasing the alternating screening-cycle frequency, o. modulator frequency.

Malan and Schanland, 1950, (ref. 12) were also interested in rapid response, and used a method similar to the above. They used a stator made of eighteen studs arranged in a circle and rotated over them a plate with eighteen corresponding holes.

But Smith, 1954, (ref. 14) used a modified sector type field mill to obtain rapid response. The stator was made of two sets of circle sectors, A and B, as shown in figure 10.

Figure 10

The rotor was made identical to one of the stator sets which when rotated produced an alternating current from each stator set. These two signals, which are exactly out of phase, were synchronized and added. With this vane configuration of rotor and stator, the area exposed to the electric field was always constant. Therefore, the limit

on response time was imposed by the electronics of the instrument and not by the frequency of the screening cycle. Smith was successful in recording a varying electric field up to a frequency of 22 kcps with a screening-cycle frequency of only 120 cps.

A much more complete list of early instruments with their particular characteristics is given in the next chapter in table I along with references for those who desire more details.

The most recent field mills have been designed by Nanevicz, Vance, and Wadsworth at the Stanford Research Institute (S.R.I.) in 1966, figure 11, (ref. 13) and by Odam and Forrest at the Royal Aircraft establishment in 1969, figure 12, (ref. 4).

The S.R.I. instrument uses a unique dual stator and rotor system as shown in figure 13. One stator and rotor set is used in a conventional fashion to measure the unknown electric field while the other set is used to provide a reference signal. That is the reference stator and rotor set is charged to an average d.c. potential.

As the rotor vanes pass by the stator vanes, they vary the stator-to-ground capacitance thus modulating the stator voltage about its mean d.c. value. Thus a reference a.c. signal is generated and the maximum amplitude of the reference signal is synchronized with the maximum amplitude of the field signal.

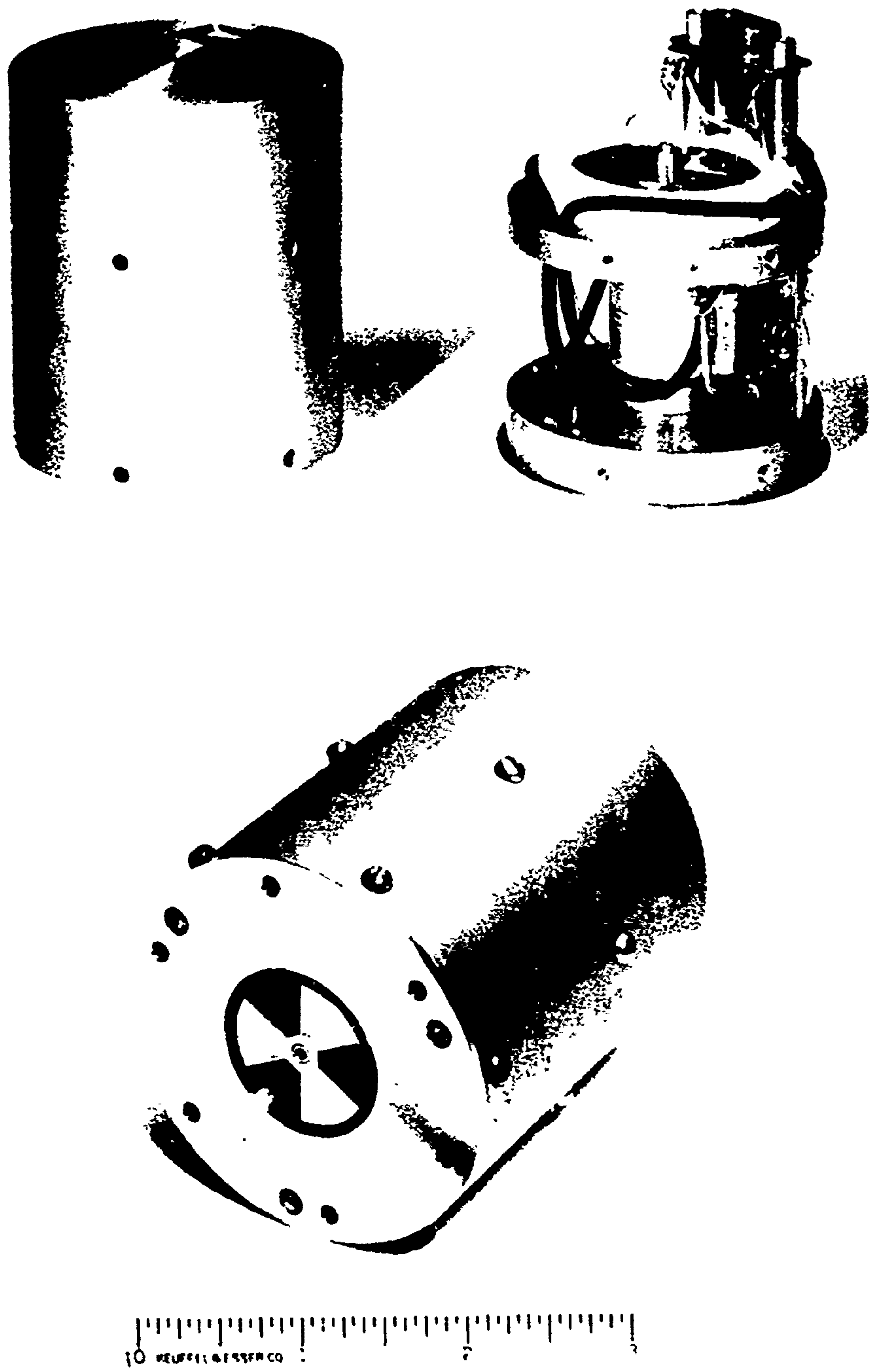

FIGURE II– S.R.I. FIELD MILL, 1966

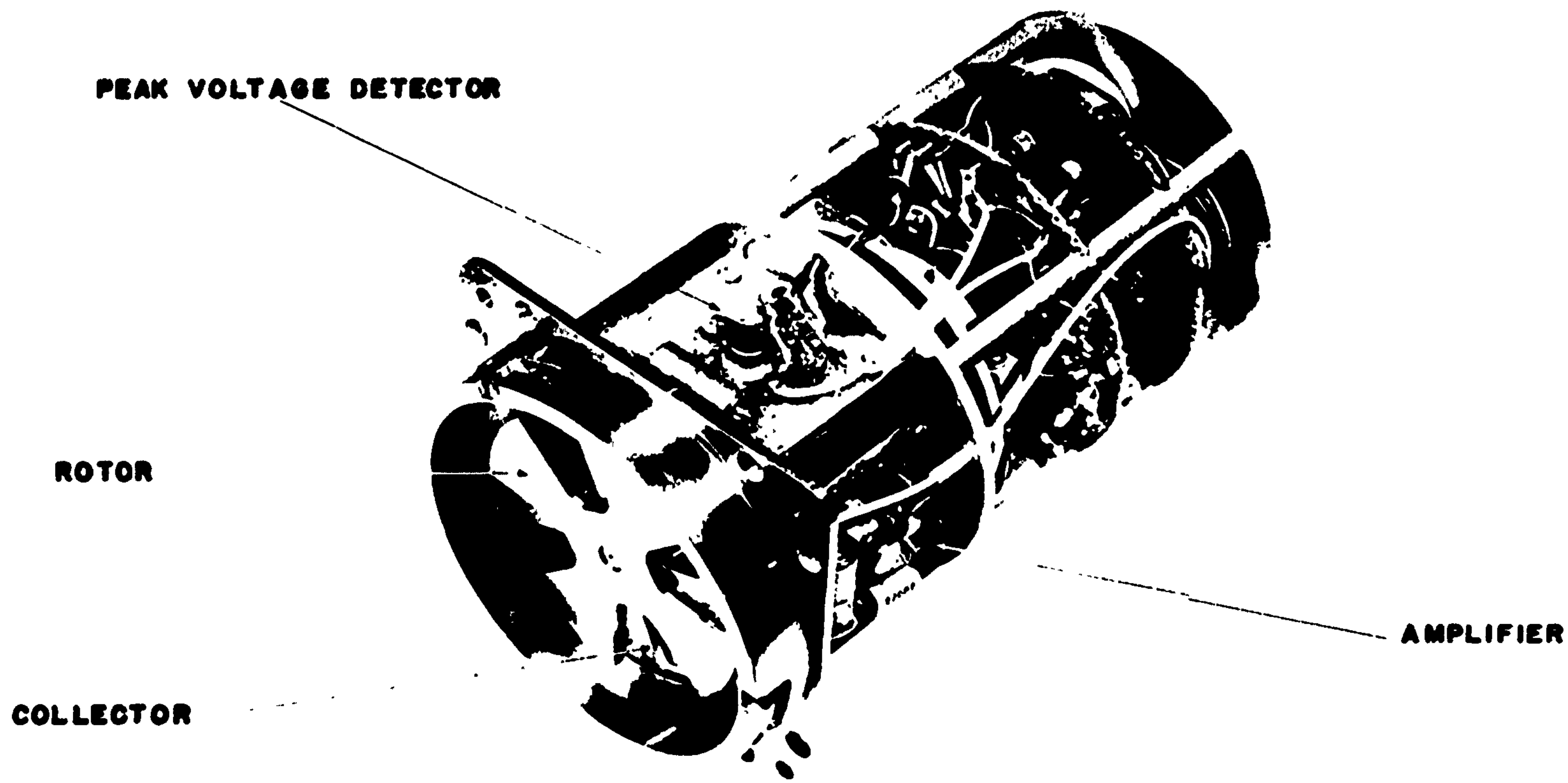

FIGURE 12 – ROYAL AIRCRAFT ESTABLISHMENT FIELD MILL, 1969

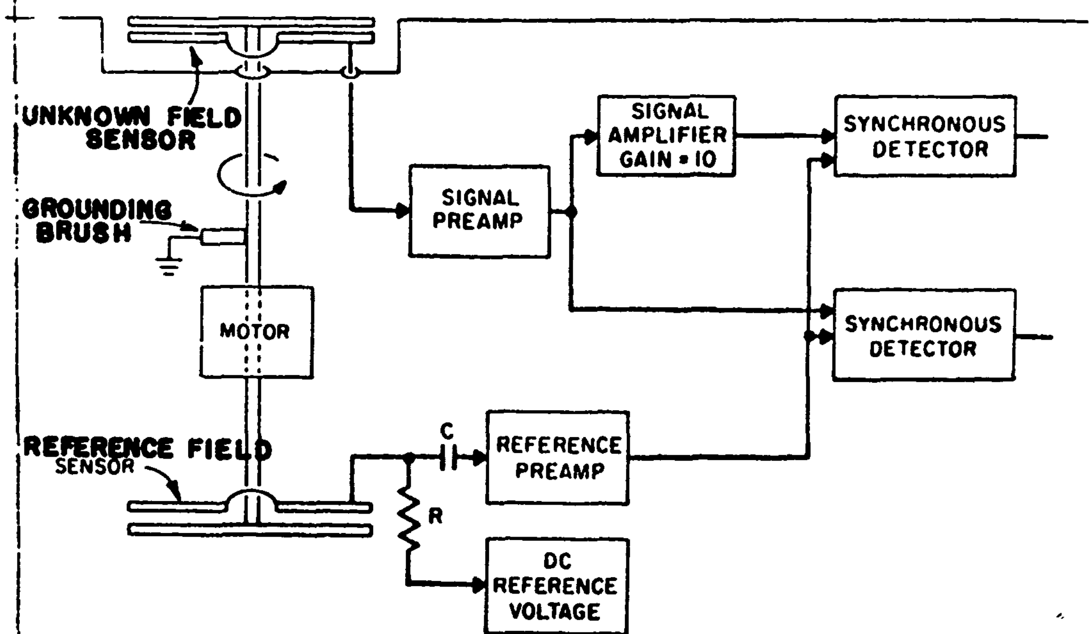

FIGURE-13-BLOCK DIAGRAM OF S.R.I. INSTRUMENT

Now, the polarity of the unknown electric field is determined by comparing the phase of the reference signal with the field signal by the use of synchronous detectors. If the phase of the field signal is 180° out of phase with the reference signal, the negative half-cycles of the field signal are passed, and if the field and reference signals are in phase, the positive half-cycles are passed. This output is then rectified and displayed on a center-zero meter.

The S.R.I. instrument used a two channel d.c. output which corresponded to electric field ranges of ± 50 Kilovolts/meter and ± 500 Kilovolts/meter.

The Royal Aircraft Establishment instrument is of conventional design. It uses a permanent magnet a.c. generator to produce a reference signal used in the polarity determination circuits, figure 14. The measurable electric field range of this instrument was ± 400 volts/meter to ± 1000 kilovolts/meter with an accuracy of better than 10% for fields greater than 2 kilovolts/meter.

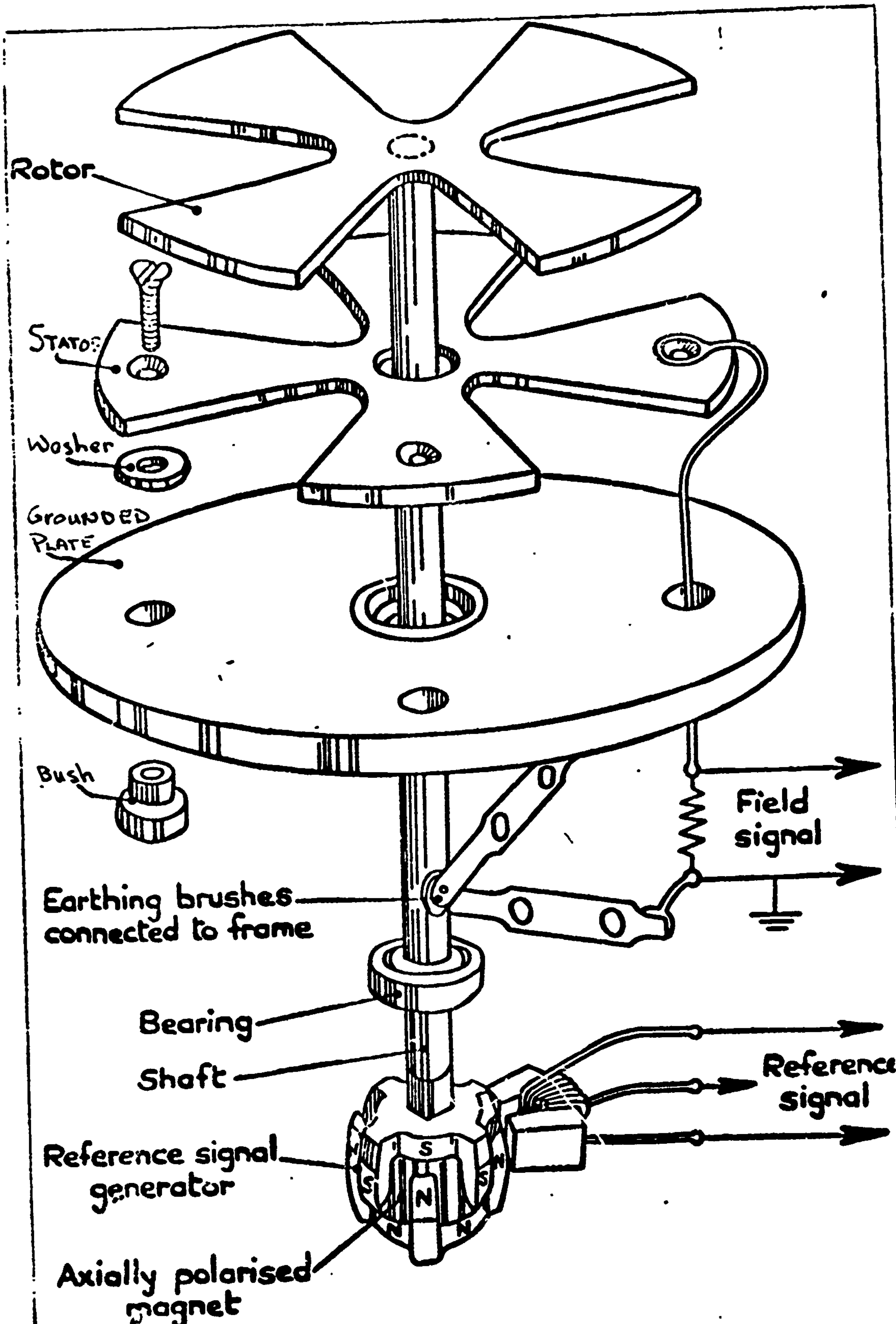

FIGURE 14-BLOCK DIAGRAM OF ROYAL AIRCRAFT INSTRUMENT

IX - SUMMARY OF BACKGROUND MATERIAL

The basic operating principle of a field mill is the alternate screening and exposing of a conductor to an electric field thereby inducing an alternating current, whose maximum amplitude is given by $\bar{D} = -\rho s$. When the above current is applied to a high impedance, it produces a voltage whose amplitude is proportional to the electric field strength.

The governing equation that indicates the design parameters of importance is

$$V = \frac{\epsilon A}{2C} \bar{E} \qquad (12)$$

$$\text{if } w^2C^2R^2 \gg 1$$

where:

V = Output peak-to-peak voltage of the field mill

ϵ = permitivity

A = maximum exposed area

E = electric field strength

C = capacity of stator, amplifier and all stray inputs

Equation (12) is a very simple expression, but it is impractical to employ due to electric field fringing effects.

Many different field mill designs have been developed. Table I attempts to list, in chronological order, these instruments and their design characteristics. This table presents by no means a complete list of instruments.

Table I - "Chronological List of Previous Field Mill Designs & their Characteristics"

Builder and Year		Conductor	Wave Form (Vane Shape)	Range	Method of Determining Polarity
1925 Matthias	(12)	R(otating)	S(ine)		independent
1932 Kirkpatrick	(3)	R	S		rectified by commutator
1932 Kirkpatrick & Miyake	([illegible])		S		rectified by commutator
1932 Gunn	(5)	R	S		rectified by commutator
1933 Macky	(11)	F(ixed)	T(riangular)	± 1000 v/m	independent
1933 Barnwell & van Voorhis	([illegible])	F	T		from null voltage polarity
1935 Henderson, Goss & Ross	(7)	R	S		rectified by commutator
1936 van Atta et. al.	(13)	F	S		independent
1937 Macky	(11)	F	T	0 - ±400 v/m	independent
1937 Thomas	(12)	R	S		rectified by commutator
1935 Schuchard	(12)	R	S		rectified by commutator
1937 Feldenkrais	(12)	R	S		rectified by commutator
1938 Neubert	(12)	R	S		independent
1939 Workman & Holzer	(20)	F	T	0 - 100 Kv/m	rectified by commutator

Builder and Year			Conductor	Wave Form (Vane Shape)	Range	Method of Determining Polarity
1940	Trump et. al.	(16)	F	T	0 - $\pm$1500 v/m	independent
1942	Rangs	(12)	F	S		zero shift
1943	Lueder *	(12)	F			asymmetry in wave form
1944	Kasemir	(12)	R	S		independent
1948	Waddel	(19)	F	T	0 - 400 Kv/m	rectified by commutator
1949	Clark	(1)	F	T	0 - 10,000 v/m	rectified by commutator
1950	Cleveland	(12)	F	T		
1950	Von Kilinski	(12)	F	T		rectified by commutator
1950	Malan & * Schonland	(12)				asymmetry in wave form
1952	Accardi	(12)	F	S		zero shift
1953	Cross	(2)	F	T	0 - 160 v/m	rectified by commutator
1954	Smith *	(18)	F	T	0 - 16,000 Kv/m	
1954	Mapleson & Whitlock	(12)	F	T S	0 - +250 v/m $\pm$75 v/m	phase sensitize detector phase sensitize detector
1962	Tona-Cornell	(17)	F	T	0 - $\pm$50 Kv/m	commutator
1966	Nawevicz et. al.	(13)	F	T	0 - $\pm$500 Kv/m	zero shift

Builder and Year		Conductor	Wave Form (Vane Shape)	Range	Method of Determining Polarity
1969 Forrest & Adam	(4)	F	T	0 - ±1000 Kv/m	synchronous detector
1971 Evans	(#)	F	T	0 - ±16,000 v/m	modified Harnwell method

+ Numbers in parenthesis refer to references listed in bibliography

* Instruments have very rapid response to a varying electric field.

To be discussed in part two of this investigation

X - DESIGN SPECIFICATIONS

After many tests on three field mill prototypes, see appendix I, the final design of the field mill was constrained by the following specifications.

The fixed conductor, or stator, field mill design concept would be employed.

A Keithley Electrometer model 610C would be used as a high input impedance amplifier in order that the condition $w^2C^2R^2 \gg 1$ would be satisfied in equation 12.

The field mill would be able to determine the magnitude and polarity of an unknown electric field.

The field mill will be used in a wind tunnel whose airstream is ladden with dust. Therefore, the instrument must be completely sealed to protect the motor used to power the rotor vane, and it must be aerodynamically shaped.

The field mill should be designed to make approximately point measurements of an electric field so that an electric field gradient can be determined.

The rotor shaft should be electrically grounded so that a minimal amount of noise is created.

Any insulating material was to be shielded in order that static charge would not be deposited on it. Bound static charge on insulators would create a very serious error voltage as explained in appendix 1.

And finally, the field mill was to be designed to mount in the existing x-y positioner used in the wind tunnel.

XI - FIELD MILL DESIGN AND INSTRUMENTATION

A - Initial Design and Instrumentation

The design was governed by the specification that the field mill should make approximately point measurements of an electric field. Therefore, the stator and rotor vanes must be made as small as possible. From the prototype tests in appendix one, the investigator felt that the smallest practical rotor and stator diameter, to produce a relatively noise free signal that would be of sufficient magnitude to calibrate accurately, was one-half (½) inch.

After determining the size of the rotor and stator, the field mill was designed as shown in figures 16 and 17. The above design can be divided into three parts, the holder section, the barrel section, and the vane head section.

The barrel section was designed to taper from 1 7/8 inch to 3/4 inch in order to mount the small d.c. motor used to power the rotor vane. The center of the barrel section was bored out to ¼" in diameter and two Torrington B-24 precision needle bearings were pressed in place. These bearings were used to mount the rotor shaft, which was made from 1/8" diameter drill rod. The motor shaft and rotor shaft were coupled by a piece of tygon tubing epoxied in place. The center bore of the barrel section from the

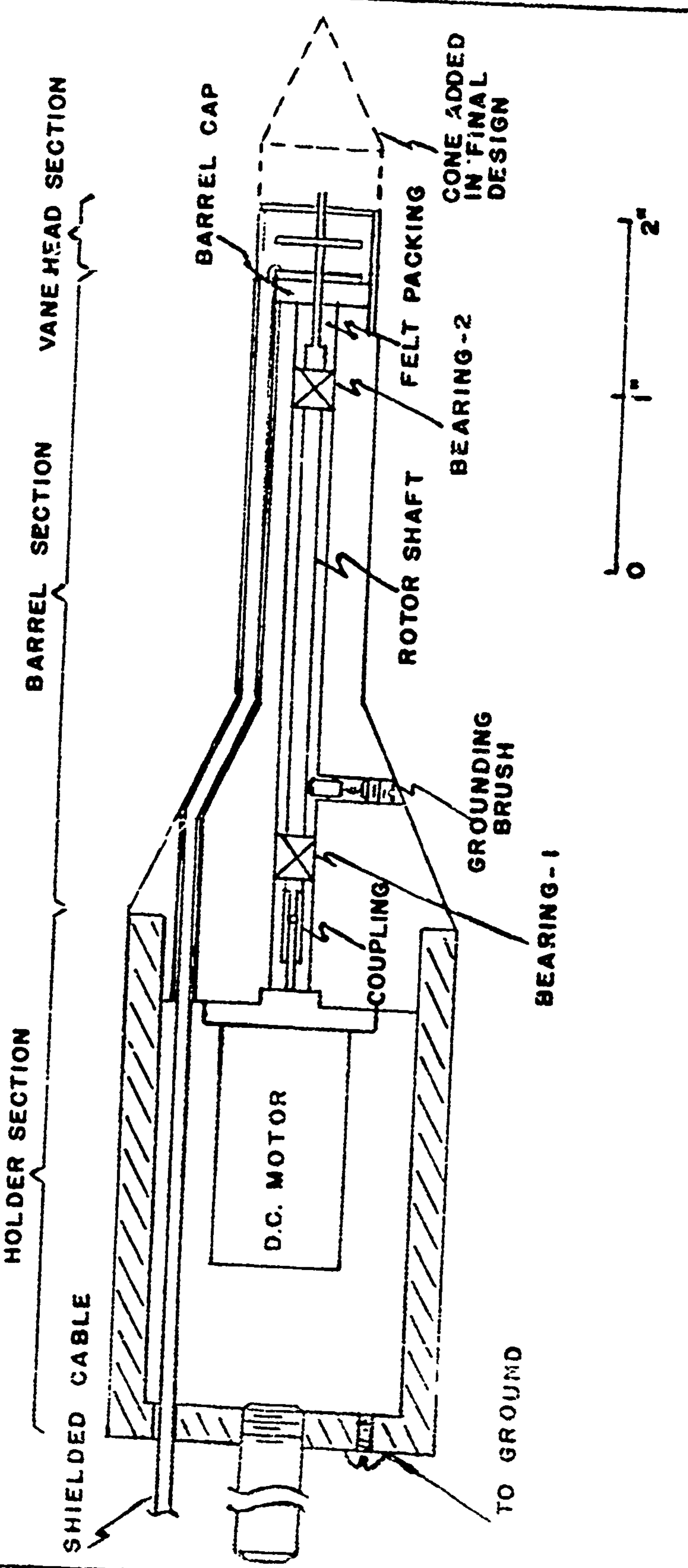

FIGURE 16— FIELD MILL DESIGN

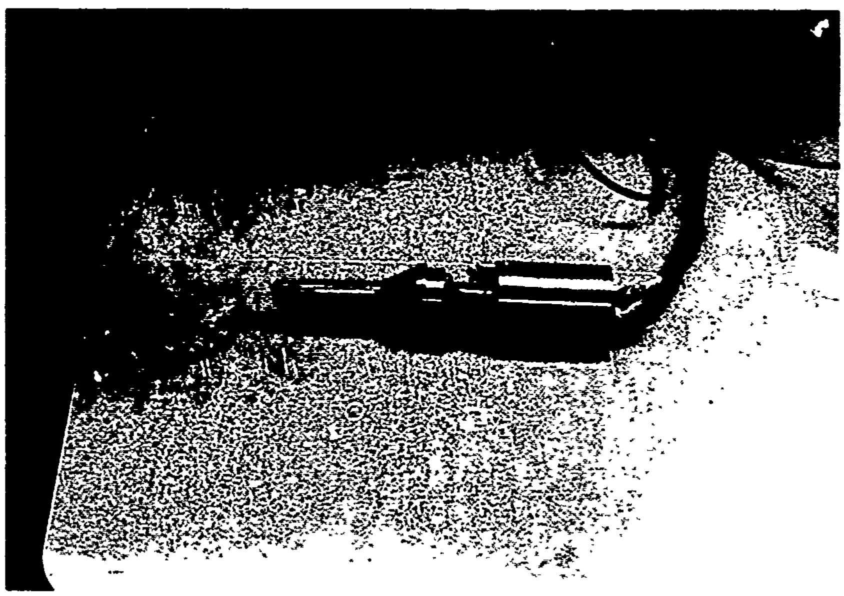

FIGURE 17— FIELD MILL GENERAL DESIGN

number 2 bearing to the barrel cap was packed with felt to protect the bearings from dust contamination. The barrel cap was then screwed in place to seal the shaft and bearing and to act as a mounting plate for the vane head section.

A slot was milled on the outer surface of the barrel so that a shielded cable, and other wires, could reach the vane head section without disturbing the flow. These wires were cemented in the slot, and the slot was painted with conducting silver paint to eliminate the insulation problem. Finally the rotor shaft was grounded by two opposed spring loaded carbon brushes.

The holder section was designed to seal the d.c. motor and to provide a 3/8" diameter shaft to enable the field mill to be mounted in the existing x-y positioner used in the wind tunnel. All holes drilled to allow wires to come out of the holder section were sealed to again guard against dust contamination.

Two different vane head sections were designed for the field mill. The first vane section as shown in figures 18 and 19 was made very similar to the one used on prototype No. 3 (see appendix 1). It consisted of a stator and rotor made of alternate quadrants of a ½ inch diameter circle punched from 10 thousandths brass shim stock. The stator

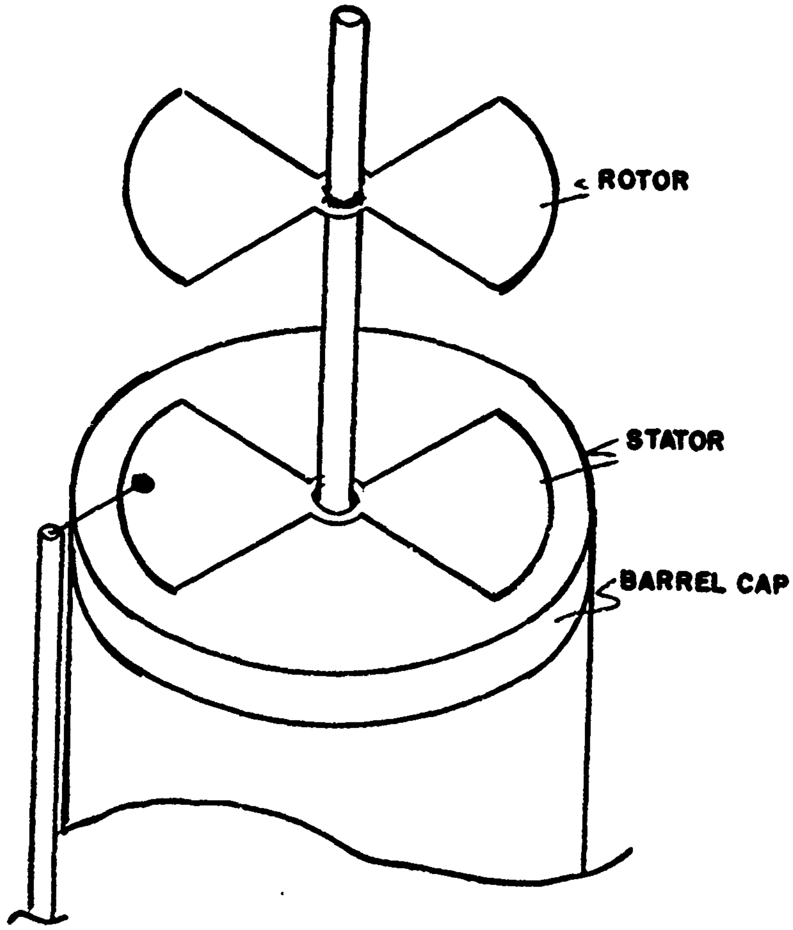

FIGURE 18 — TWO VANE HEAD SECTION

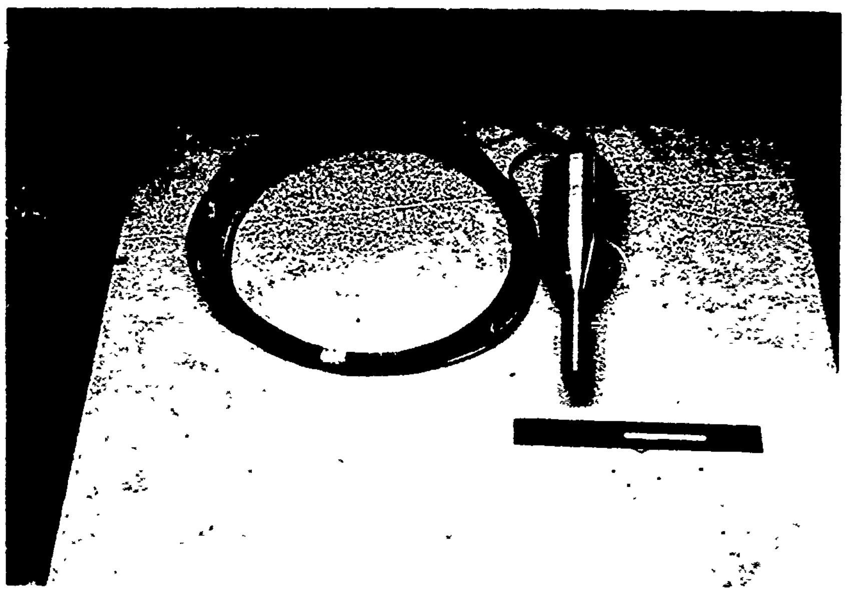

FIGURE 19—FIELD MILL WITH TWO VANE HEAD SECTION

was mounted on the barrel cap but electrically insulated from it, and the core wire of the shielded cable was soldered to the stator. The rotor was spaced approximately $\frac{1}{4}$" directly above the stator and soldered to the rotor shaft. The above vane configuration was tested (see chapter XII, Calibration of Field Mill) to determine if the present field mill had the same performance characteristics as prototype No. 3.

The second vane head section was identical in concept to the one used by Harnwell and Van Voorhis (ref. 6) as presented in chapter VIII, page 18. This vane head section consisted of three vanes as shown in figures 20 and 21. The stator vane was now a full $\frac{1}{2}$" diameter brass disk. It was mounted on the barrel cap but electrically insulated from it. Directly above the stator was a rotor made of alternate quadrants of a $\frac{1}{2}$" diameter brass disk. Directly above the rotor and identical in shape to the rotor was a "shadow vane". The shadow vane was connected to a double throw switch which either grounded the vane or connected it to a fixed potential.

When the shadow vane was grounded, it screened an equal area of the stator from the electric field lines. Hence, the three vane configuration operates in an identical manner to the two vane configuration if the shadow vane is grounded.

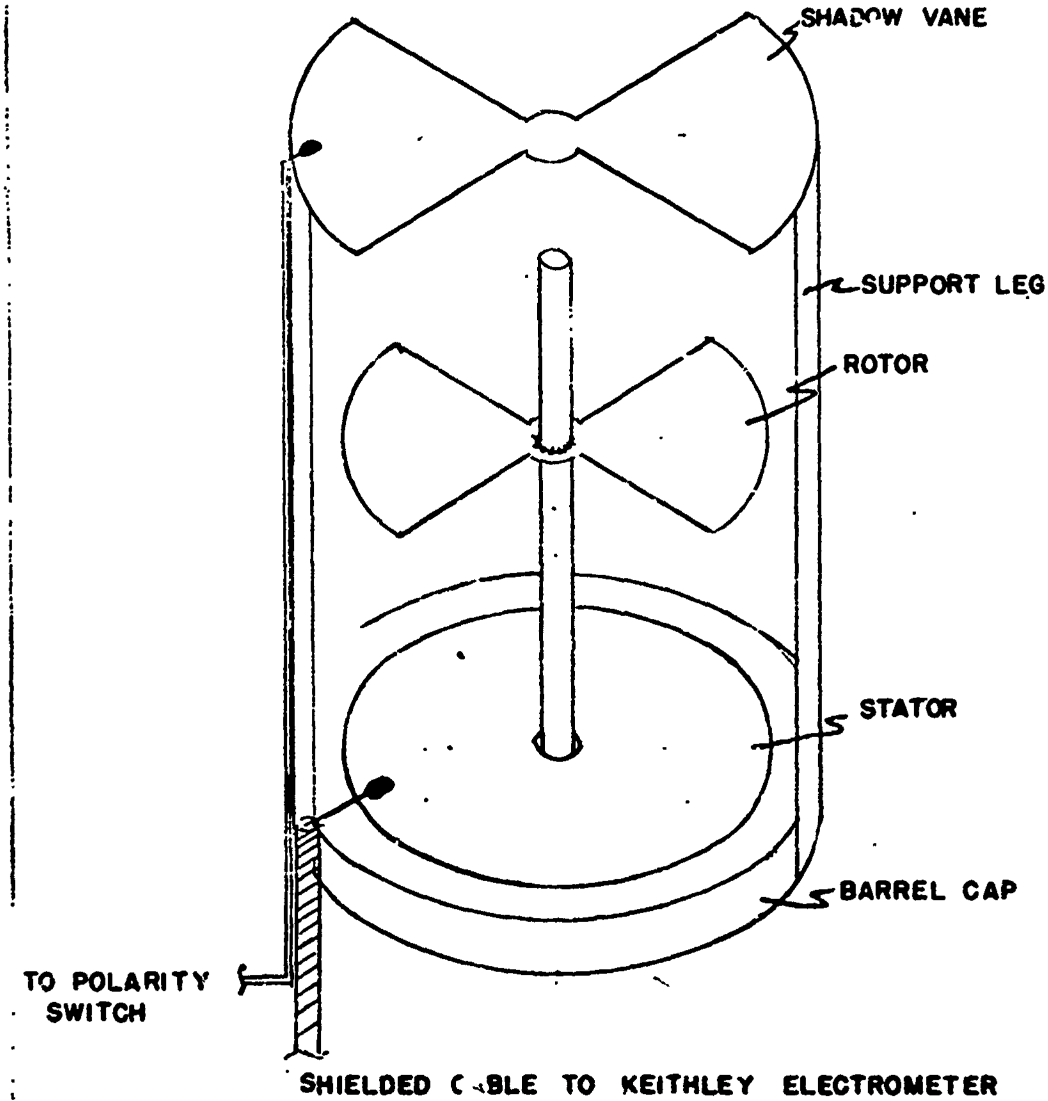

FIGURE 20 – THREE VANE HEAD SECTION

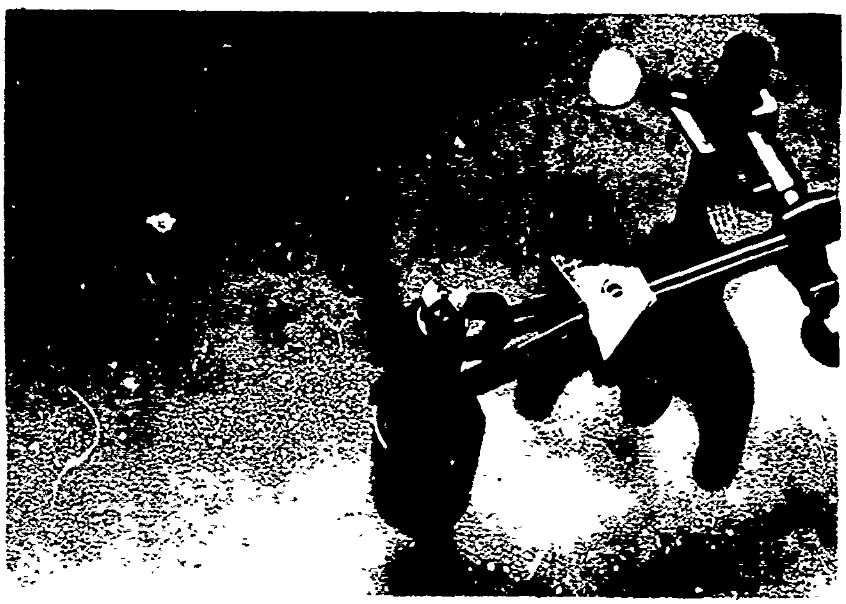

FIGURE 21 - FIELD MILL WITH THREE VANE HEAD SECTION

If a potential is applied to the shadow vane, an electric field is created between it and the stator, which changes the potential on the screened portion of the stator. The potential on the screened area of the stator, which is zero in the grounded state, can be thought of as the reference potential, V ref. If the unknown electric field to be measured has the same polarity as the applied electric field, the V ref will have been raised and a decrease in the signal voltage will result when compared to the voltage obtained with V ref = zero (grounded). The reverse will happen when an unknown field of opposite polarity is present. The V ref. will be lowered, and the signal voltage will be greater than if the shadow vane was grounded.

Hence, this vane head section was designed to operate with the shadow vane grounded to obtain the magnitude of the unknown electric field. The polarity of the electric field would then be determined by applying a fixed potential to the shadow plate and observing whether the output voltage increased or decreased.

In both of the above vane head sections a shielded cable connected the stator to the input of the Keithley Electrometer. The recorder output terminal of the Keithley was then connected to a Tektronic 502 A oscilloscope and a Dana 3800 digital multimeter. The oscilloscope was

used to monitor the field mill waveform in order that one could detect when the Keithley amplifier was saturated. The Dana multimeter was used as a digital read out of the rms voltage. A schematic of the three vane head section and instrumentation is presented in figure 22. Figure 23 shows the field mill with the three vane head section, polarity switch, motor battery, and polarity battery. And figure 24 shows the field mill in the test capacitor along with the associated instrumentation.

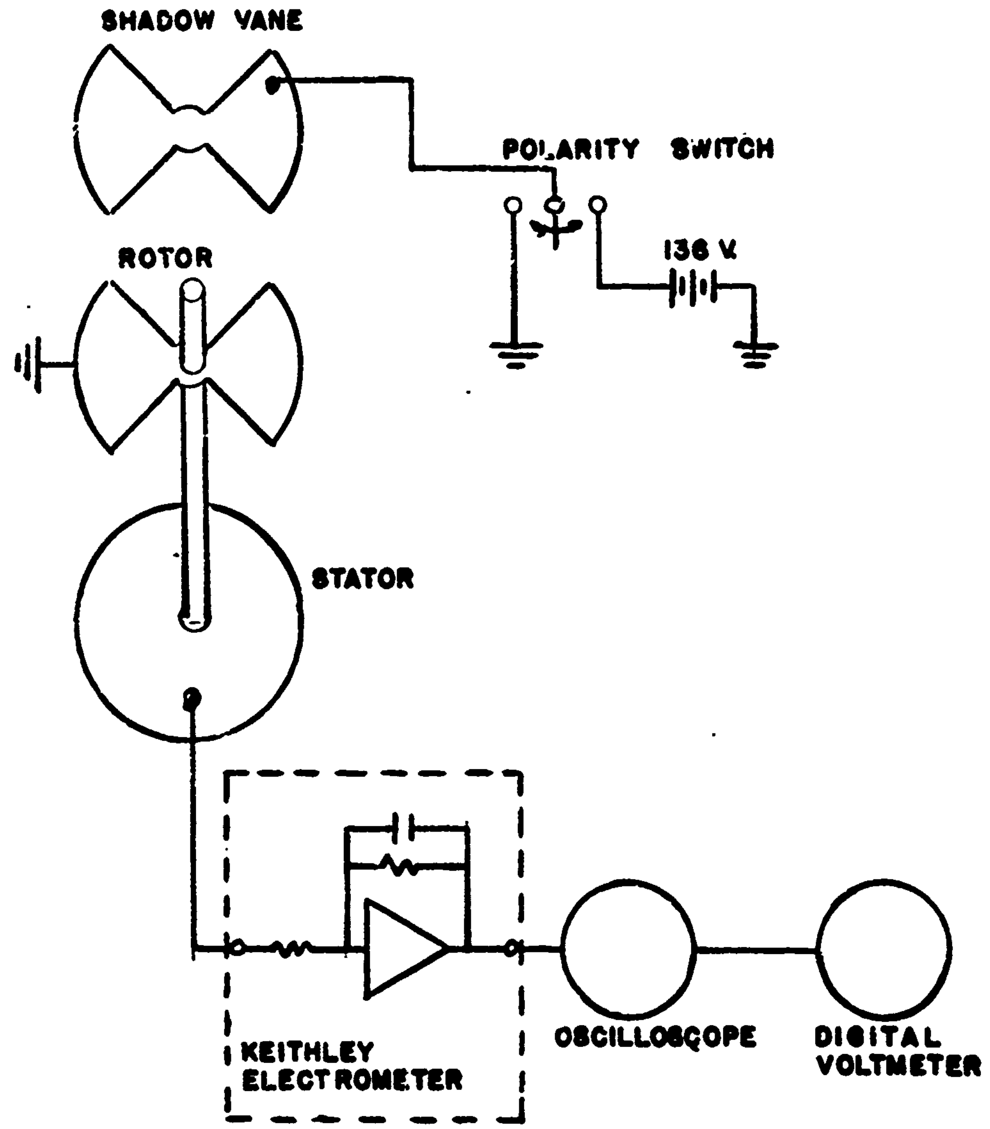

FIGURE 22-SCHEMATIC OF INSTRUMENTATION FOR THE THREE VANE HEAD SECTION

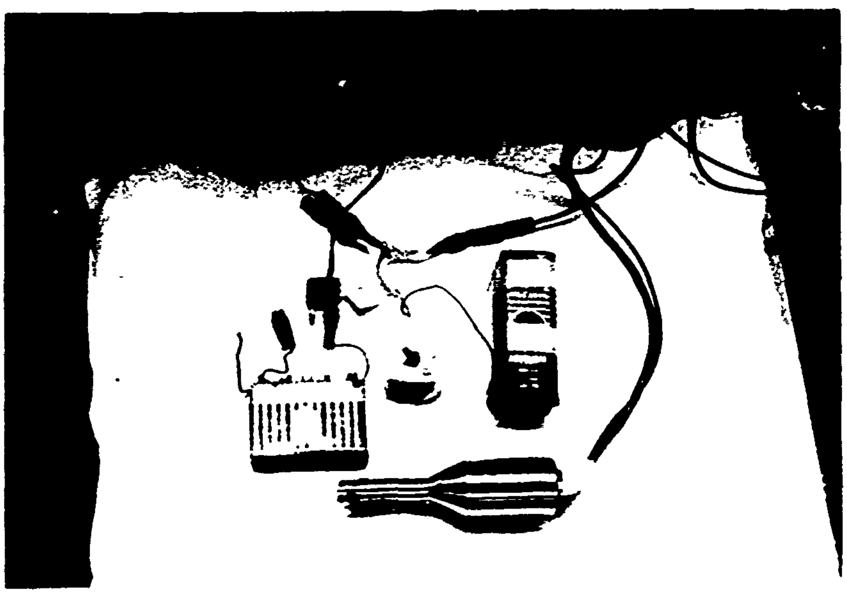

FIGURE 23— FIELD MILL WITH POLARITY SWITCH

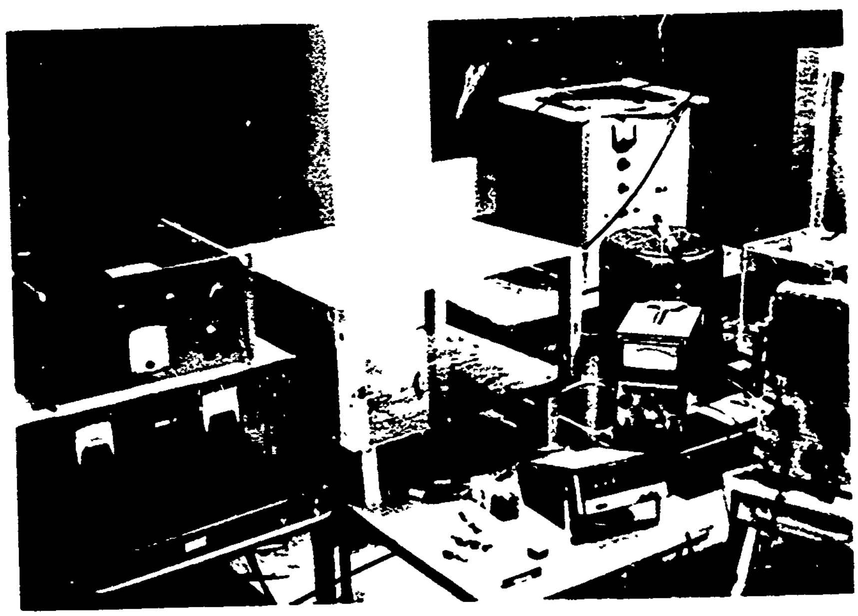

FIGURE 24–FIELD MILL IN TEST CAPACITOR WITH INSTRUMENTATION

B - Design and Instrumentation Modifications

Several preliminary tests in the wind tunnel, which are treated extensively in chapter XII, dictated two modifications to the initial design of the field mill.

First, the three vane-head section of the field mill was protected from direct impact of dust particles by a grounded cone placed 3/8 inch directly above the shadow vane, as shown in figures 16 and 25.

Second, the Dana multimeter was replaced by a Brush lightbeam oscillograph model 16-2308-00 and a high pass filter. Figure 26 shows a schematic of the filter where C is a coupling capacitor and R_{in} is the input impedance of the oscillograph.

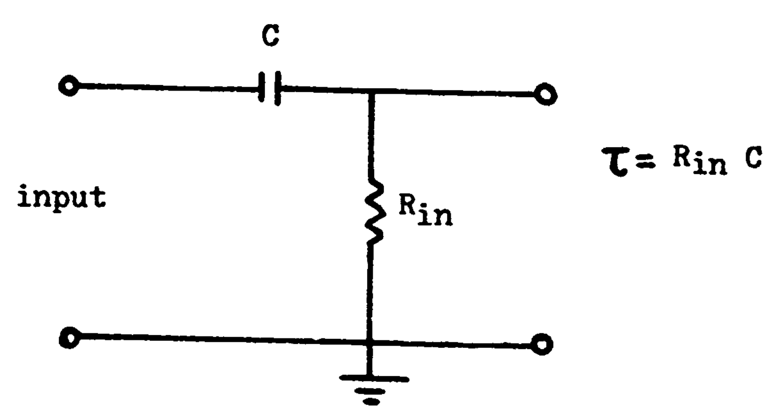

Figure 26

FIGURE 25—FIELD MILL WITH DEFLECTING CONE

Since the input impedance of the oscillograph varied with gain setting, the filter was designed for a gain of four or ten with a corresponding input impedance of 2000 ohms. It was desired to cut off all frequencies from zero to approximately 30 cps. The value of the coupling capacitor was then determined by

$$C = \frac{1}{R_{in}\, 2\pi f}$$

Therefore, a coupling capacitor of 0.022 μf was necessary.

XII - CALIBRATION OF THE FIELD MILL

A - Calibration Apparatus

In order to evaluate the performance of the field mill and determine the experimental relationship between the unknown electric field to be measured and the field mill output voltage (that is calibration of the instrument), test apparatus was needed to create a large uniform electric field.

The resulting apparatus, as shown in figure 27, consists of two 3'x3' aluminum plates spaced 1' apart by wooden supports. A potential was applied to these plates using a high voltage regulated d.c. power supply. Thereby creating an electric field which would be very uniform away from the edges of the plates.

The Power Designs Pacific, Inc., Model HV-1[illegible] regulated power supply was adjustable from 10 to 5000 volts, in steps of 1 volt. The power supply dial voltage settings were checked using a digital volt meter up to a maximum potential of 1000 volts and proved to be extremely accurate. Hence the electric field strength between the plates was hereafter calculated by reading the applied potential to the parallel plates directly from these dial settings and dividing this potential by the plate spacing distance. Hence the maximum field strength that could be created with this apparatus was approximately 16,000 volts per meter.

Calibration of a field mill was now a very simple matter of creating a field of known strength between the parallel plates (capacitor) and reading the field mill output peak-to-peak voltage on an oscilloscope or the rms voltage on a digital voltmeter.

The accuracy of the calibration method was influenced by only two major sources of error, electric field distortion due to the presence of the field mill and a non-steady, zero field output signal.

Distortion of the electric field was due to the fringing effects caused by the grounded rotor plate and the stator plate. In order to minimize this the field mill vanes were placed as close as possible to the grounded capacitor plate. This method was finally taken to the limit by boring a hole in the grounded capacitor plate just large enough for the vane head section of the field mill to pass through.

The varying zero field signal problem was caused by the design of earlier field mill prototypes. These design problems are discussed extensively in appendix 1 and reference 12. Appropriate design changes have been made so that the above error has been eliminated.

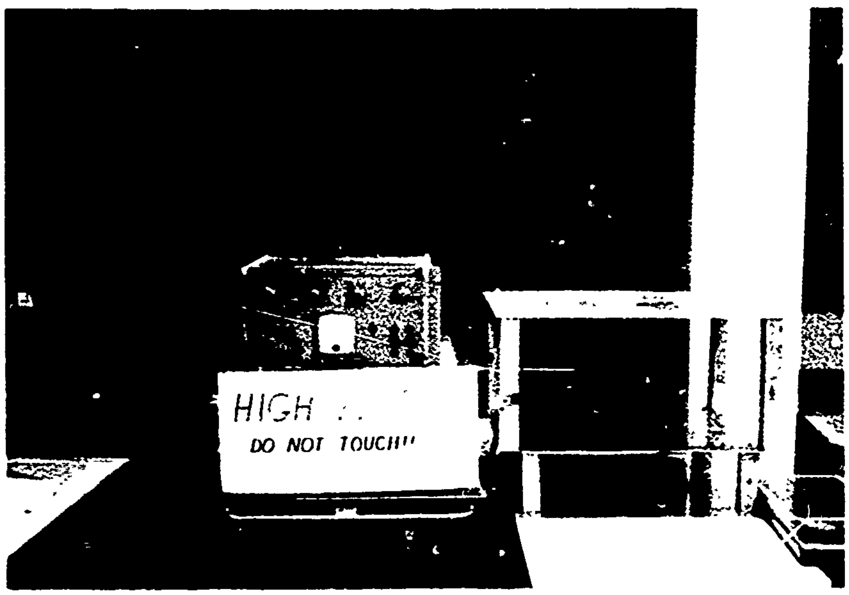

FIGURE 27–UNIFORM ELECTRIC FIELD TEST APPARATUS

B - Calibration of the Two Vane and Three Vane Head Sections

The initial field mill design using the two different vane head configurations were now calibrated in the test capacitor. Since previous work with field mill prototypes, appendix 1, employed a two vane configuration, the initial design of the field mill was first checked by calibrating its two vane head section. Then, if an extremely linear calibration curve resulted, as was the case with the prototypes, the grounding brushes, electrical connections, etc. of the field mill would be demonstrated to be performing well.

The first time the two vane field mill was placed in the test capacitor with an applied electric field of 4000 volts per meter only noise was present in the output signal. An examination of the grounding brushes showed that lubricant from the needle bearings had contaminated them. The brush contact area of the rotor shaft was cleaned thoroughly with acetone and the 4000 volt per meter field reapplied. The output signal was now of sine wave form with no noise distortion. The frequency of the output signal was approximately 90 cps. The frequency of the field mill output signal should be twice the angular velocity of the rotor vane. The angular velocity of the rotor vane was approximately 2600 rpm which would correspond to a signal frequency of 86.6 cps. Hence, the above signal was generated by the alternate exposure and screening of the stator by the rotor.

Having established the above fact, the two vane head section was calibrated from 0 to 9,000 volts per meter as shown in figure 28. As can be observed from the calibration curve, the experimental relationship between the field mill output voltage and the applied electric field was extremely linear. This extreme linearity demonstrated that the field mill system was performing perfectly. Therefore, the next phase of development was started by replacing the two vane configuration with the three vane configuration.

As stated before, the three vane configuration would provide means to determine the polarity of an unknown electric field. The field mill with a three vane configuration was placed in the test capacitor and the polarity switch, as shown in figure 22, was set on ground. The instrument was then calibrated from 0 to 10,500 V/m as shown in figure 29. Since the ideal principle of operation of the above configuration, with the polarity switch set on ground, is identical to the two vane configuration, the two calibration curves should ideally be identical. Both curves are linear but the slopes of the curves are not identical and the ratio of the slope of the two vane to the three vane configuration was 1.43. The decrease in output signal amplitude of the three vane section was caused by the screening of the non-ideal fringing electric field lines, by the support legs of the shadow vane, from

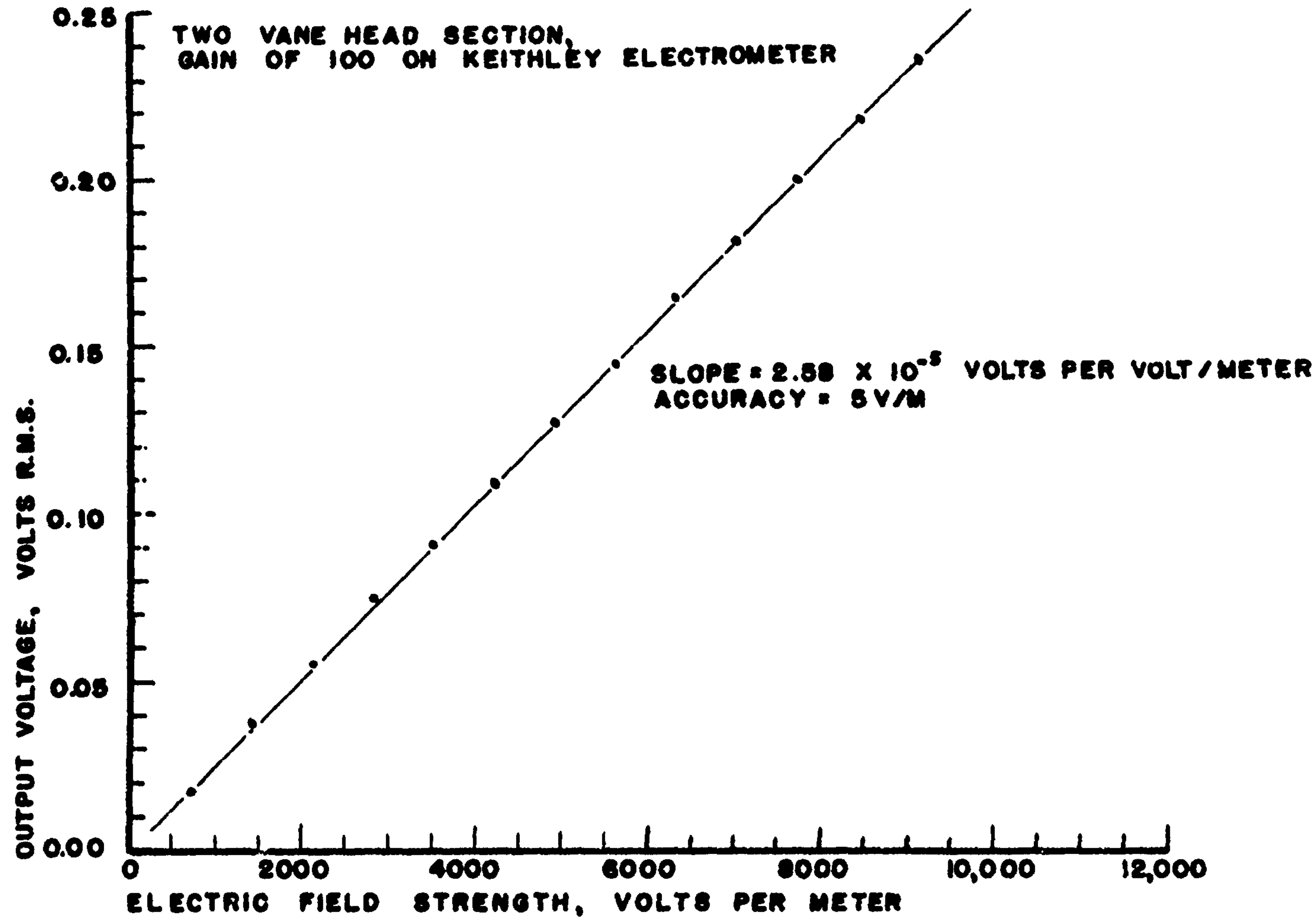

FIGURE 28 - FIELD MILL CALIBRATION CURVE

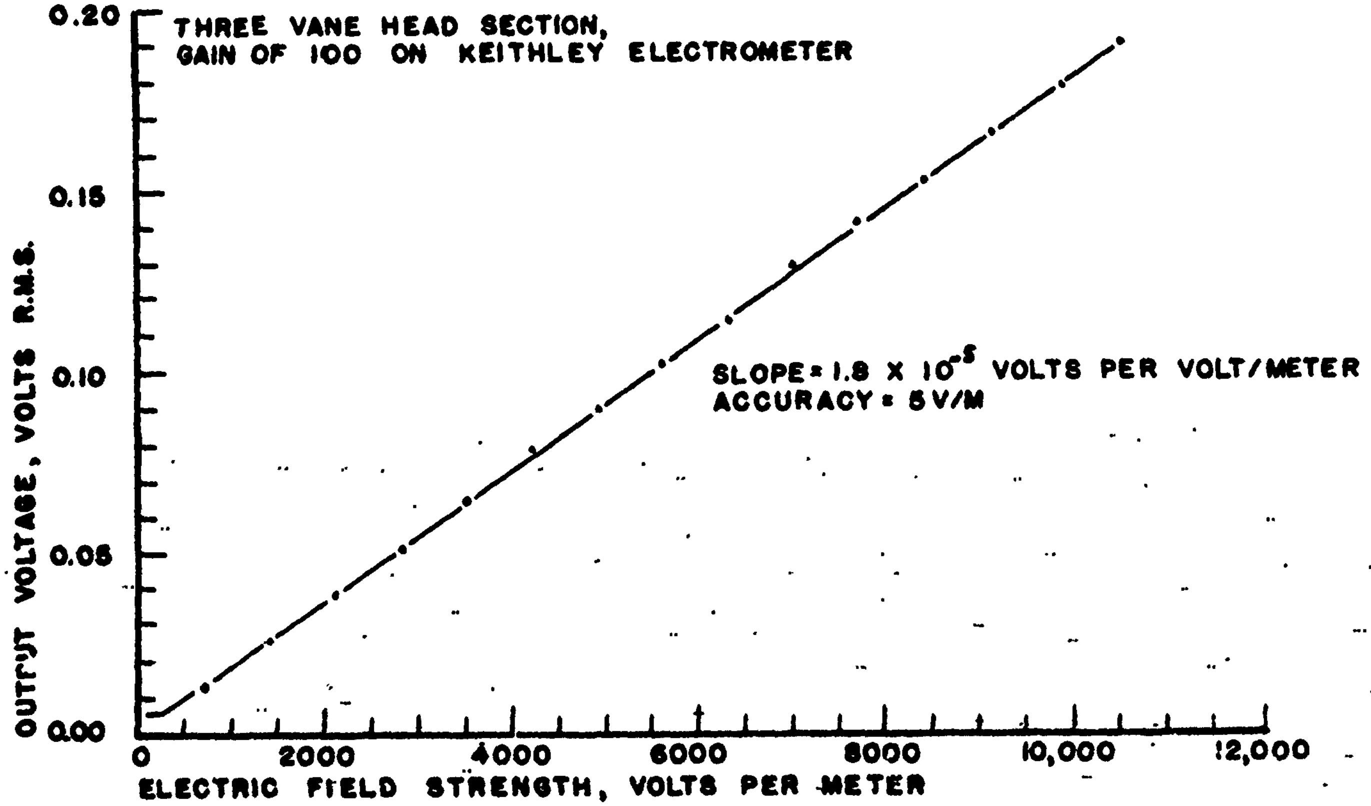

FIGURE 29 – FIELD MILL CALIBRATION

the stator. Hence the two vane configuration had more electric field lines, or electric flux density lines, terminating on the stator than the three vane configuration. As shown previously, the amplitude of the output signal of a field mill is directly proportional to these flux lines. Therefore, the signal amplitude of the three vane configuration should be less than that from the two vane.

Having demonstrated that the three vane configuration was performing in an equivalent, if not identical, manner to the two vane configuration, the polarity determination method was ready to be evaluated. Both test capacitor plates were grounded to create a zero electric field and the field mill polarity switch was set on V. This switch position applies a voltage of -136 V.d.c. to the shadow vane which creates an electric field between the shadow vane and the stator vane. The output signal of the field mill caused by this electric field was approximately 40 millivolts a.c., but the signal wave form was not a perfect sine wave as before. This distortion of the sine wave was to be expected since the field created by the shadow vane was extremely non-uniform when compared to the field created by the test capacitor. However, the above wave form was judged acceptable.

The polarity switch was again set on ground and an electric field strength of 1400 volts per meter was created in the test capacitor. The field mill output signal

for this field was 0.026 V.a.c. The polarity switch was now set at V and the output voltage was 0.061 V.a.c. Hence, the difference in output voltage was 0.035 V.a.c. Since the polarity of the two electric fields present were different, the output voltage, as explained in Chapter XI, should increase as observed. Thus, the three vane method of polarity determination was demonstrated to perform as hypothesized.

C - Calibration of the Three Vane Head Section With Deflecting Cone Using the Brush Lightbeam Oscillograph and High Pass Filter.

When the high pass filter was added to the Brush recorder, it caused some attenuation of the 90 c.p.s. field mill signal. In order to relate the amplitude of the recorded traces on the oscillograph to voltage, it would be necessary to adjust the gain adjust screw on the front of the oscillograph to compensate for the attenuation. However, this adjustment would have to be made for each different gain setting used. If one wished to change rapidly from one gain setting to another, a different amplifier would have to be used for each gain setting. Since the oscillograph was being used on many different projects, the gain adjustments would have to be checked each time the apparatus was used. The above adjustment would be very time consuming. And a readjustment of the gain would introduce a new source of error into the electric field measurements.

But the linear charateristic of the calibration curve shown in figure 29 demonstrated that the field mill was performing according to specifications. Therefore, to circumvent the disadvantage of changing the gain of the oscillograph, it was calibrated directly in volts per meter for each individual desired gain setting. The above was accomplished by placing the field mill in the

test capacitor and recording the field mill signal on oscillograph traces at selected values of electric field.

For the present investigation the oscillograph was calibrated at a gain setting of 10, only. The calibration data is presented in Chapter XVI and figure 30 shows the resulting calibration curve.

The polarity switch was also checked during the above calibration as shown in figure 31. The field mill output amplitude (peak-to-peak) for a + 14,300 Volt per meter electric field was 2.48 inches with the polarity switch set on ground. With the polarity switch set on V the amplitude (peak-to-peak) was 3.2 inches and the difference between the two signals was 0.88 inches. The reference trace (67 V.d.c. applied to shadow vane) with zero field, and the polarity switch on V, showed an amplitude of 0.9 inches. Therefore, the polarity of an unknown electric field is positive when an increase in amplitude is obtained with the polarity switch set on V. And, the polarity of an unknown electric field is negative when a decrease or <u>no change</u> is obtained with the polarity switch set on V. One would obtain no change in signal amplitude if the unknown electric field was negative and its amplitude was one-half the polarity amplitude.

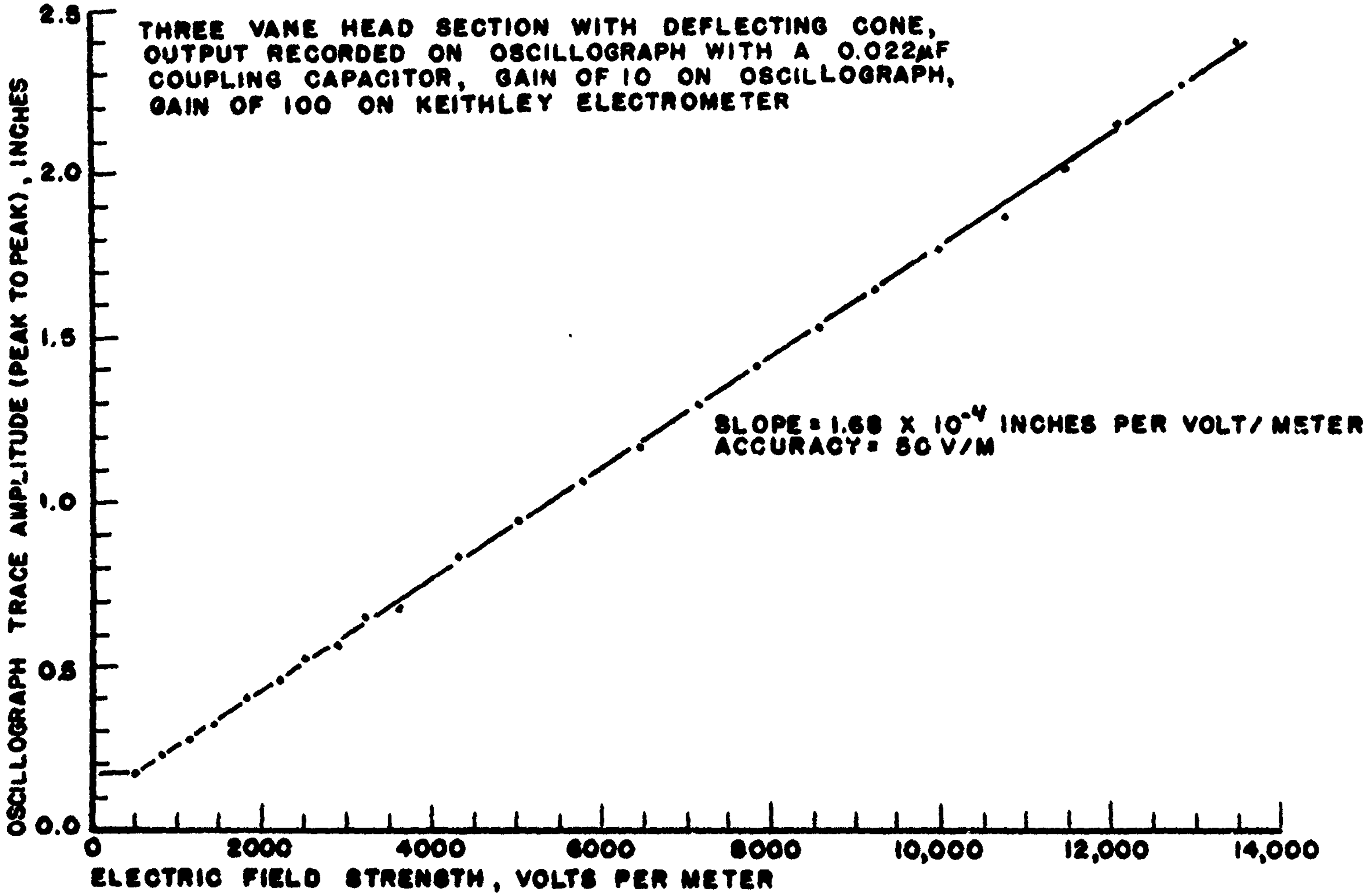

FIGURE 30 — FIELD MILL CALIBRATION CURVE

XIII - DEVELOPMENT AND TESTING

A - Preliminary Wind Tunnel Test

The development work w on the field mill prototypes, appendix 1, did not result in any conclusions as to the performance of the field mill in a wind tunnel whose airstream contained a particulate suspension. The effect of direct impact of particles on the stator and the direct transfer of charge to the stator and Keithley amplifier from these particles was unknown. Therefore, the field mill with the calibrated three vane head section was placed in the wind tunnel to determine the effects of the above.

The field mill was clamped to an extendable rod which was fixed firmly in the tunnel. The polarity switch of the field mill was set on ground. The wind tunnel was started and the airflow accelerated to a velocity of 140 fps with no dust being introduced. The field mill signal was approximately zero for the above conditions. The dust feeding system was now activated and roughly two pounds per minute of dust was fed into the airstream. The field mill signal as displayed on the oscilloscope was now nothing but noise with extremely high peaks. One could not distinguish any signal with a frequency of 90 c.p.s. Also, the Keithley amplifier would continually saturate. These drastic effects were hypothesized to be caused by the impact of dust particles on the stator which would cause

charge or current pulses. If this hypothesis was correct, the angular velocity of the rotor could be reduced to zero and the output signal would not change. The rotor vane was stopped and the oscilloscope display did not change. Therefore, it would be necessary to protect the stator from direct impact of dust particles.

B - Design Modifications

It was an extremely difficult design problem to make a cover to protect the vane head section of the probe. If a dialectric was used, in order that the electric field lines could pass through the cover, the static charge build-up on the dialectric, as experienced in the prototype field mills, would create an unacceptable error voltage. If one used a conductor to completely cover the vane section, the electric field would terminate on the cover and the stator would be completely screened from the electric field. However, a grounded, cone shaped conductor placed far enough ahead of the vane head section would deflect the dust particles and prevent their direct impact on the stator. This cone would definitely terminate the electric field lines that were coming directly into the stator. However, the fringing electric field lines would not terminate on the cover but would curve into the stator.

Hence, a small cone was made and placed directly on top of the shadow vane. The field mill was then placed in the test capacitor and a quick calibration showed that the

output voltage was reduced approximately by a factor of 5. This was judged too drastic a signal reduction. The cone was then moved 3/8 inch above the shadow vane as shown in figure 25 and a quick calibration showed a signal reduction of only 50% which was judged acceptable. Before the field mill was placed back in the wind tunnel, the Dana Multimeter was replaced by a Brush Lightbeam oscillograph model 16-2308-00.

The field mill was placed back in the tunnel at approximately the same position as before and the airstream velocity and dust feed rate were the same as before. The field mill output signal oscillograph trace is shown in figure 32A and figure 32B shows a frequency reference signal obtained by putting the polarity switch on V with dust flow in the tunnel. As one can observe from the reference trace, the signal frequency has decreased. This was the result of a defective battery which caused the d.c. motor to run at a lower rpm. Therefore, the battery was replaced by a power supply. The signal wave form again has quite a lot of noise in it. But a close comparison will reveal a definite signal frequency equal to the reference frequency. Also the extremly high peaks of the noise that saturated the Keithley amplifier are absent. The signal trace, therefore, showed the correct trends but it would be impossible to determine the amplitude of the output signal with the reference frequency.

It was also noticed that a steady d.c. signal input was obtained from the field mill. This d.c. signal made it impossible to get a zero reference on the oscillograph trace. It was also thought that some of the signal waveform distortion might be caused by the above.

This d.c. component of the field mill signal was predicted by Nanevica, Vance, and Wadsworth (ref. 13). They assumed the field mill vanes were shaped to expose the stator in a sinusoidal fashion. Then the instantaneous charge induced on the stator, as shown previously would be

$$q = \frac{\epsilon EA}{2} \quad (1 + \sin wt)$$

They assumed the field mill load impedance was essentially capacitive if the field mill amplifier input resistance was greater than 10 times the capacitive reactance. Therefore, the instantaneous induced voltage was

$$V = q/C = \frac{\epsilon EA}{2C} \quad (1 + \sin wt)$$

where C is the capacity of the vanes and amplifier input. The above voltage can be broken up into two components; a d.c. component and an a.c. component.

$$V_{dc} = \frac{\epsilon EA}{2C}$$

$$V_{ac} = \frac{\epsilon EA}{2C} \sin wt$$

Hence for any measured electric field of strength $\overline{E}$, an induced alternating and an induced direct voltage will result. The above expression for the alternating voltage component is identical to equation 12 obtained by Mapleson and Whitlock.

In order to eliminate this d.c. component, a high pass filter or coupling capacitor was added to the oscillograph, as described in chapter XI.

C - Tunnel Tests

The field mill, with the above modifications, was placed at position #1 in the wind tunnel, as shown in figure 33.

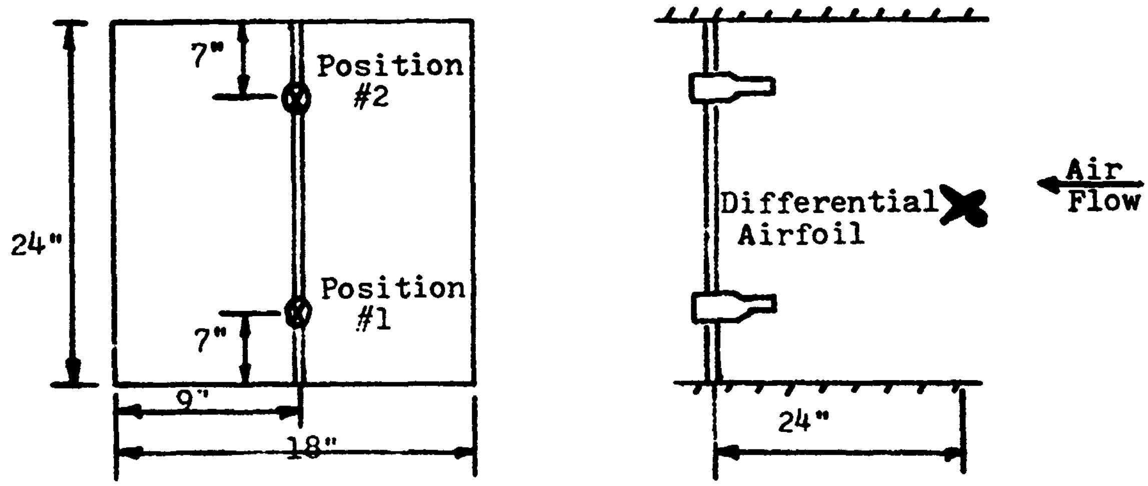

Figure 33

The tunnel air velocity was set at 140 fps and the dust was fed into the airstream at the approximate rate of 2 lb/min. Figure 34 shows the resulting oscillograph trace of the field mill output signal with an oscillograph gain of 10, a paper speed of 50 inches per second, Keithley electrometer gain of 100 and polarity switch on ground. Figure 35 shows a reference frequency trace obtained with no flow in the tunnel, the polarity switch on V, with the remaining instrument settings unchanged.

The field mill was now moved to position #2. The tunnel air velocity was set at 140 fps. Before dust was injected into the airstream a background trace, as shown in figure 36, was obtained with the polarity switch on ground and all other settings unchanged. The dust was then injected into the airstream at a reduced rate of 1 lb/min. (due to mechanical difficulties) and figure 37 shows the resulting oscillograph trace.

Next the paper speed of the oscillograph was reduced to 5 in/sec and two traces under the above airstream conditions were obtained at position #2; one with the polarity switch on ground, figure 38, and one with the polarity switch on V, figure 39.

XIV - EVALUATION OF THE FIELD MILL PERFORMANCE

A - Wind Tunnel Tests

Comparison of the oscillograph trace of the field mill output signal at position #1 with dust injected into the airstream, figure 36, and with the reference frequency trace, figure 35, demonstrates that the [illegible] cps frequency of the field mill signal has not been destroyed by noise as in the preliminary tests. Also, the noise has been reduced to such a level, that the peak-to-peak amplitude of the signal could be approximately measured. It is obvious from figure 34 that the electric field in the tunnel was not constant with respect to time. This variation in electric field was to be expected since the rate of dust injection into the airstream was not as uniform as desired.

The approximate average peak-to-peak amplitude of the field mill signal in figure 34 was 2.8 inches which corresponds to an electric field, as shown by figure 30 of 16,000 volts per meter. Since the trace in figure 34 was taken at a rate of [illegible] inches/second, the above electric field strength is not the average field strength at that location but closer to the instantaneous field strength at that location. However, the purpose of the above oscillograph trace was to prove that the field mill signal frequency was distinguishable and that an average amplitude could be approximated from the trace.

Figures 36-40 show oscillograph traces of the field mill output signal obtained with the instrument located in position #2 (figure 33). Figure 36 is a signal trace with only residual dust in the airstream. Since no distinguishable 90 cps frequency is present and the peak-to-peak amplitude of the signal is no greater than 0.2 inches, the signal can probably be attributed to noise in the system. In any case, the electric field strength would have to be equal to or less than 500 volts per meter as shown by figure 30.

Figure 37 shows the signal trace obtained with a dust feed rate of 1 lb/min into the airstream. Again, the modulation frequency of the field mill signal is easily distinguished. The approximate average peak-to-peak amplitude of the signal is 1.1 inches which corresponds to an electric field strength from figure 31 of 6000 volts per meter. Since the only variable change between figure 36 and figure 37 was the addition of dust into the airstream, one can conclude that the dust is the agent causing the electric field. From the analysis of the field mill signal trace presented in figures 35 and 37, one can conclude that the field mill will indeed satisfy the specification of measuring the magnitude of an unknown electric field.

The signal traces shown in figures 38, 39 and 40 were recorded at the rate of 5 inches per second, as compared

with the 50 inches per second for the previous traces, in order that the nature of the average electric field at a point in the tunnel could be examined and to test the electric field polarity determination method. Figure 38 shows the field mill signal obtained with the polarity switch set on ground (the same as for the previous traces). In this trace the unsteady nature of the electric field is quite obvious. In order to obtain an average amplitude of the signal that could be compared with a signal amplitude at another location, one would probably be forced to use statistical methods. However, the approximate average peak-to-peak amplitude was 1.0 inch which corresponds to an electric field of 5500 volts per meter.

Figure 39 shows the field mill signal obtained with the polarity switch set on V. A comparison of the amplitude of the signal traces in figures 38 and 39 shows that the signal amplitude has increased with the polarity switch on V. This would indicate the presence of an electric field of positive polarity. The approximate average amplitude of the signal in figure 39 was 2 inches.

Figure 40 shows the trace obtained with the polarity switch set on V (136 volts applied to the shadow vane) with no dust flow. The peak-to-peak amplitude of the polarity trace was 1.5 inches. The ideal amplitude of the signal obtained in fugure 39 would be the sum of the ampli-

tudes in figures 38 and 40 or 2.5 inches. Due to the non-steady nature of the measured electric field and the very rough approximations to the average amplitudes of the signals, the actual amplitude of figure 39 was considered acceptable. Therefore, the design specification to be able to determine the polarity of an unknown electric field was satisfied.

B - Summary and Conclusions

The field mill with the three vane head section and deflecting cone did indicate clearly the presence of an electric field in the wind tunnel when the airstream was injected with dust. The approximate average electric field strength at position #1 and position #2 in the tunnel was respectively 16,000 and 6,000 volts per meter with an indicated positive polarity at position #2. The purpose of the above measurements was to demonstrate the field mill could determine the magnitude and polarity of an unknown electric field. Since the above electric field strengths were obtained with two different dust injection rates, no hypothesis can be made about the presence of an electric field gradient.

Due to the non-steady state nature of the electric field, the magnitude of the unknown electric field in the wind tunnel was difficult to determine accurately. Statistical analysis of the field mill data will probably be necessary to determine if an electric field gradient exists and to test the effects of a vortex on the above gradient.

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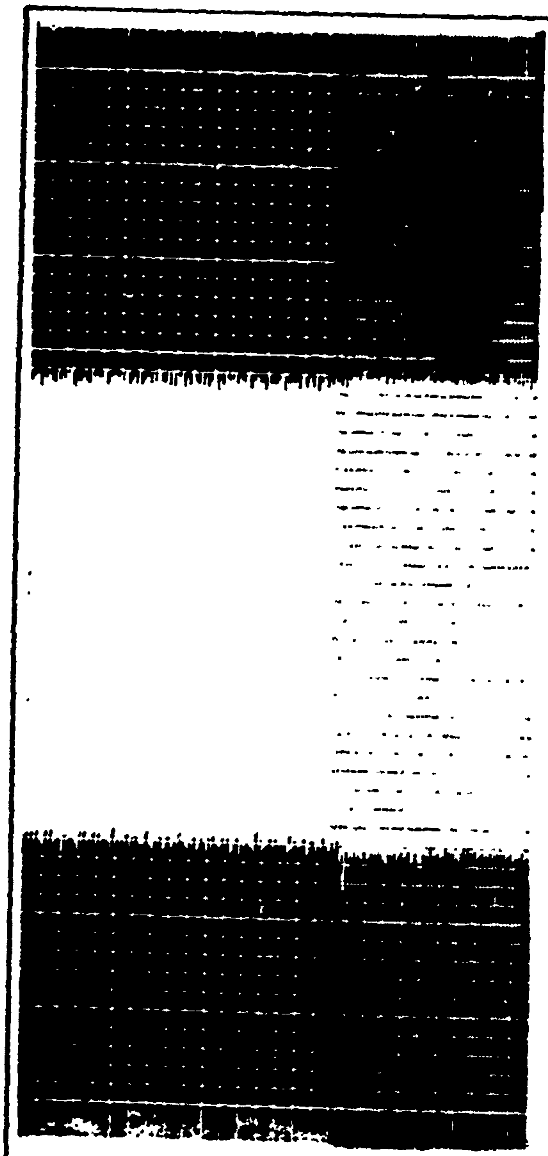
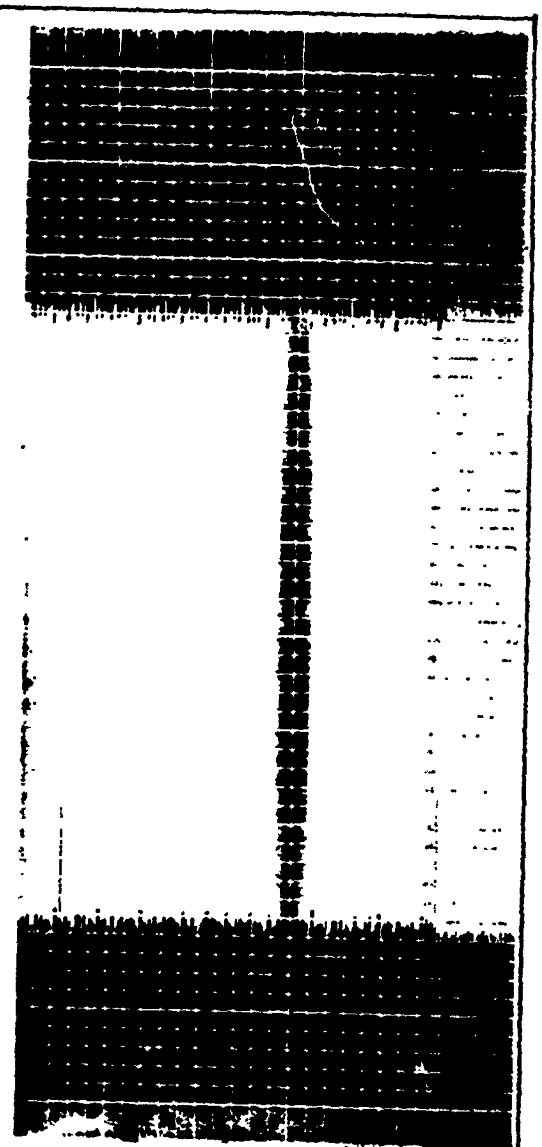
XVI - OSCILLOGRAPH TRACES



POLARITY SWITCH ON GROUND



POLARITY SWITCH ON V

FIGURE 31

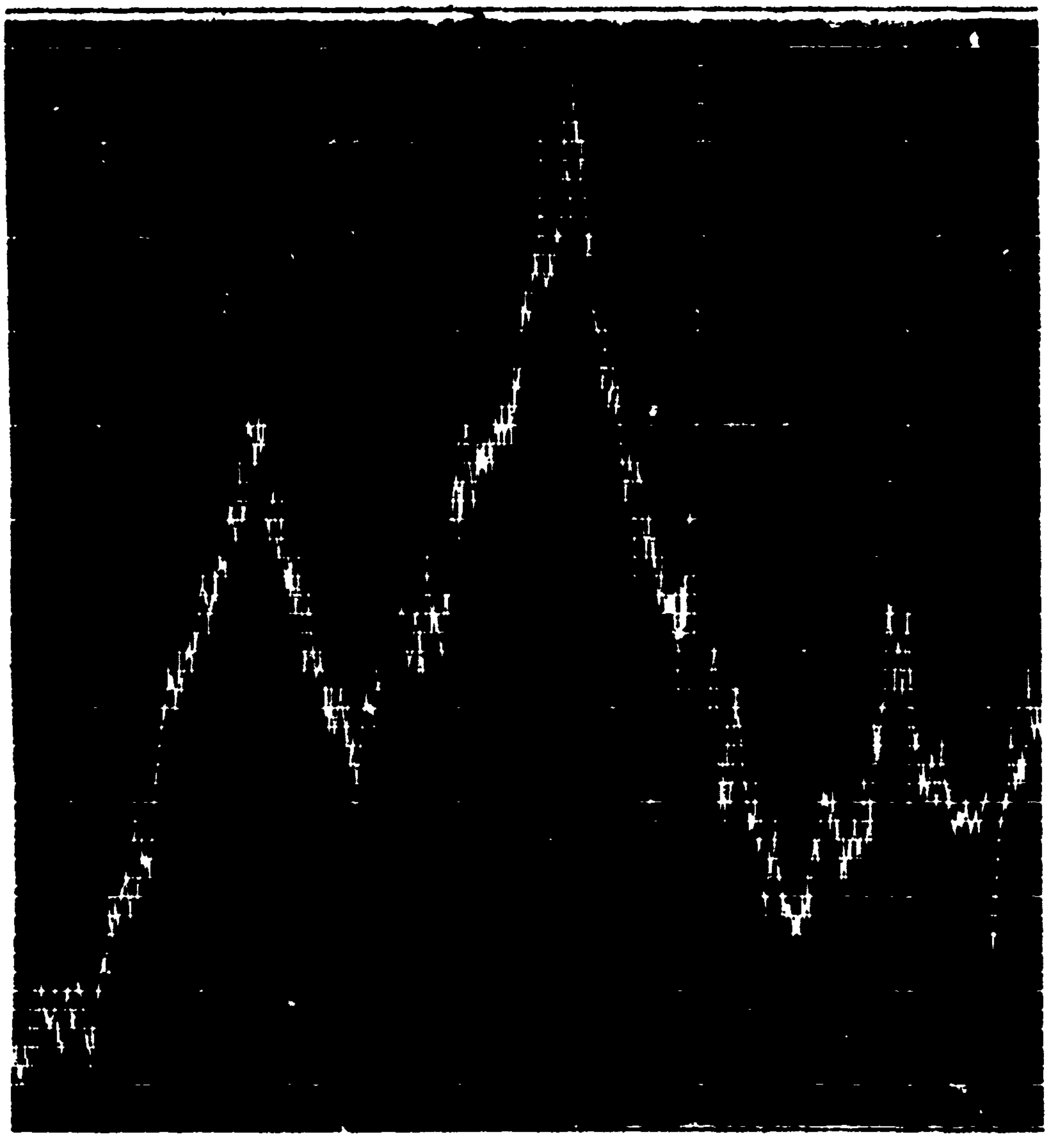


FIGURE 32A

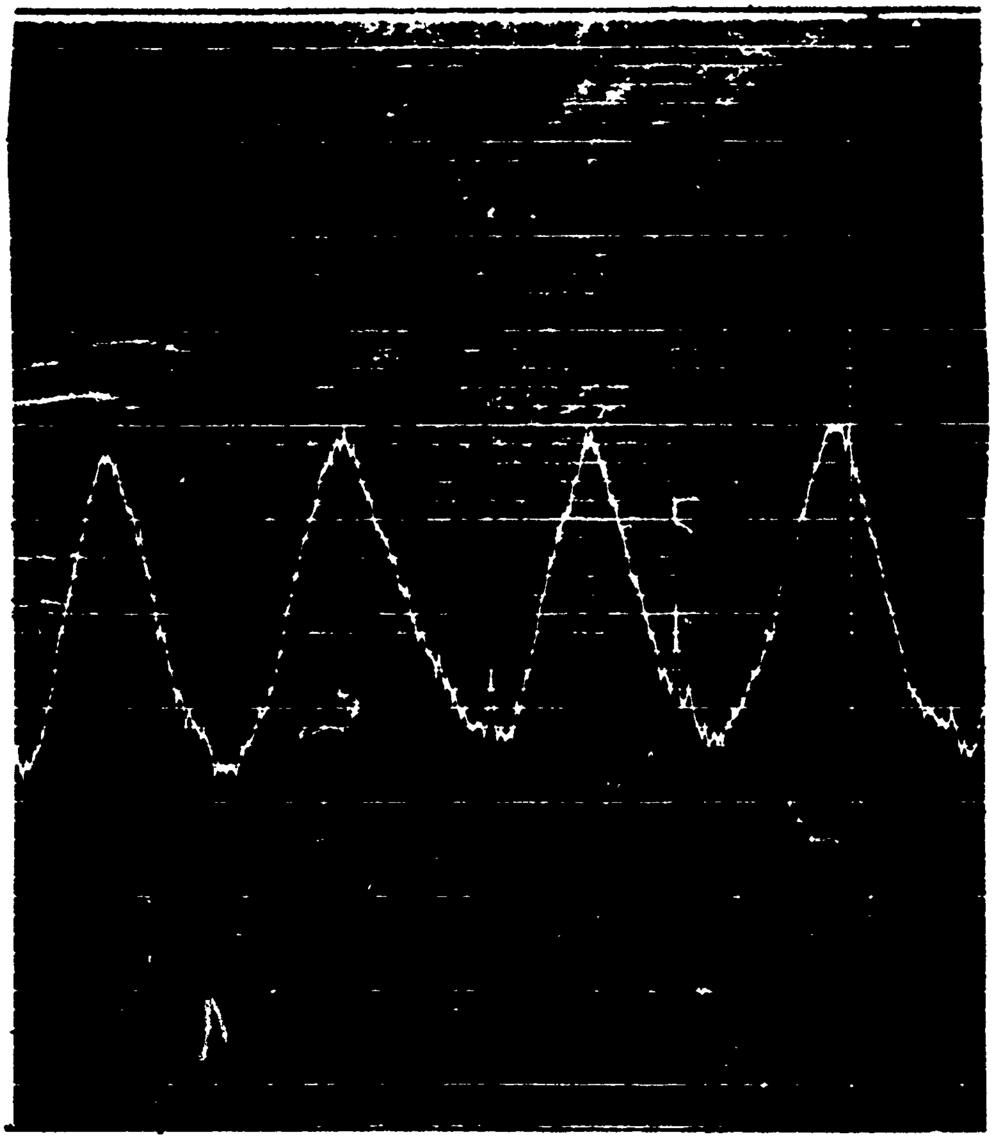


FIGURE 32B

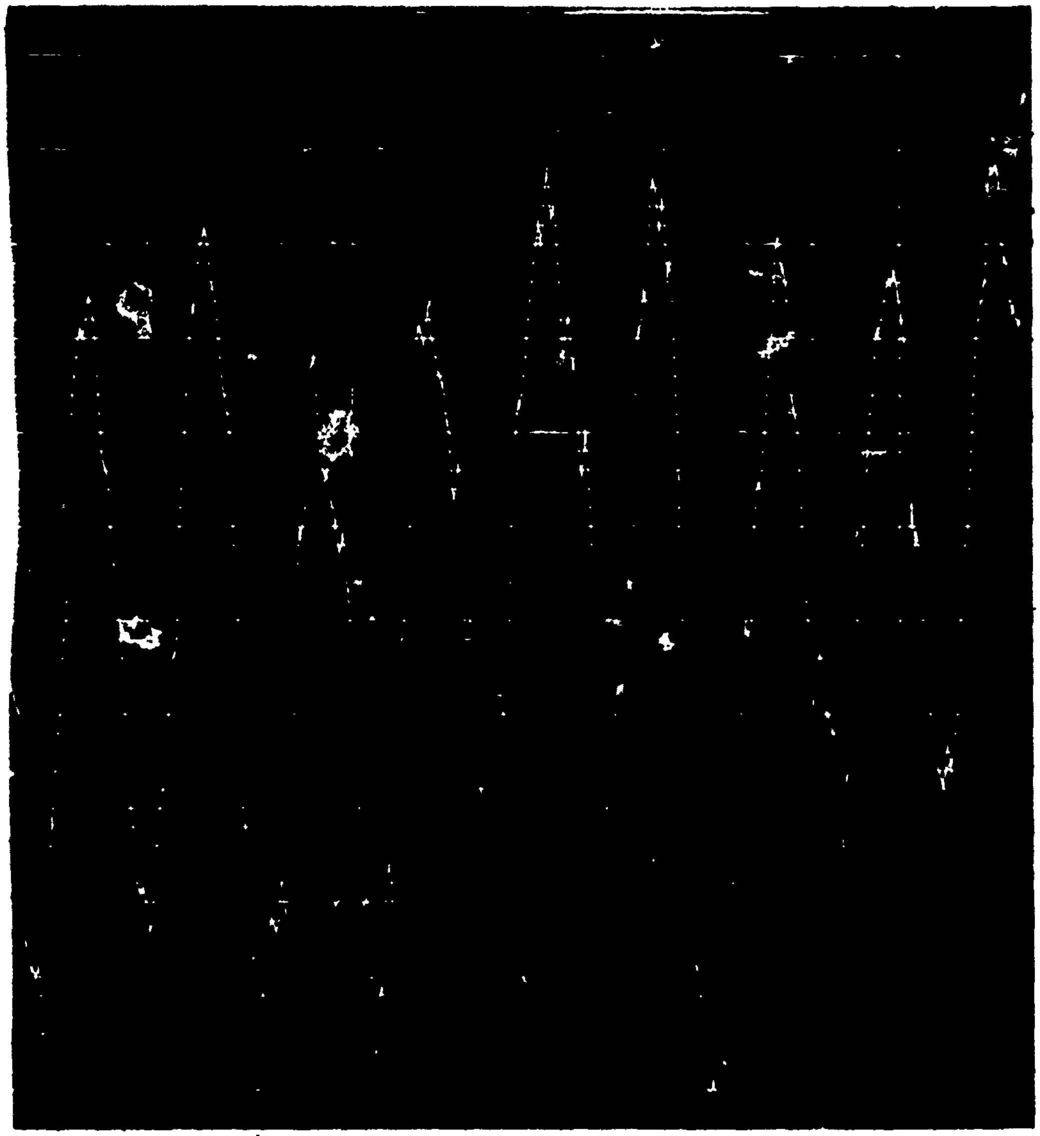


FIGURE 34

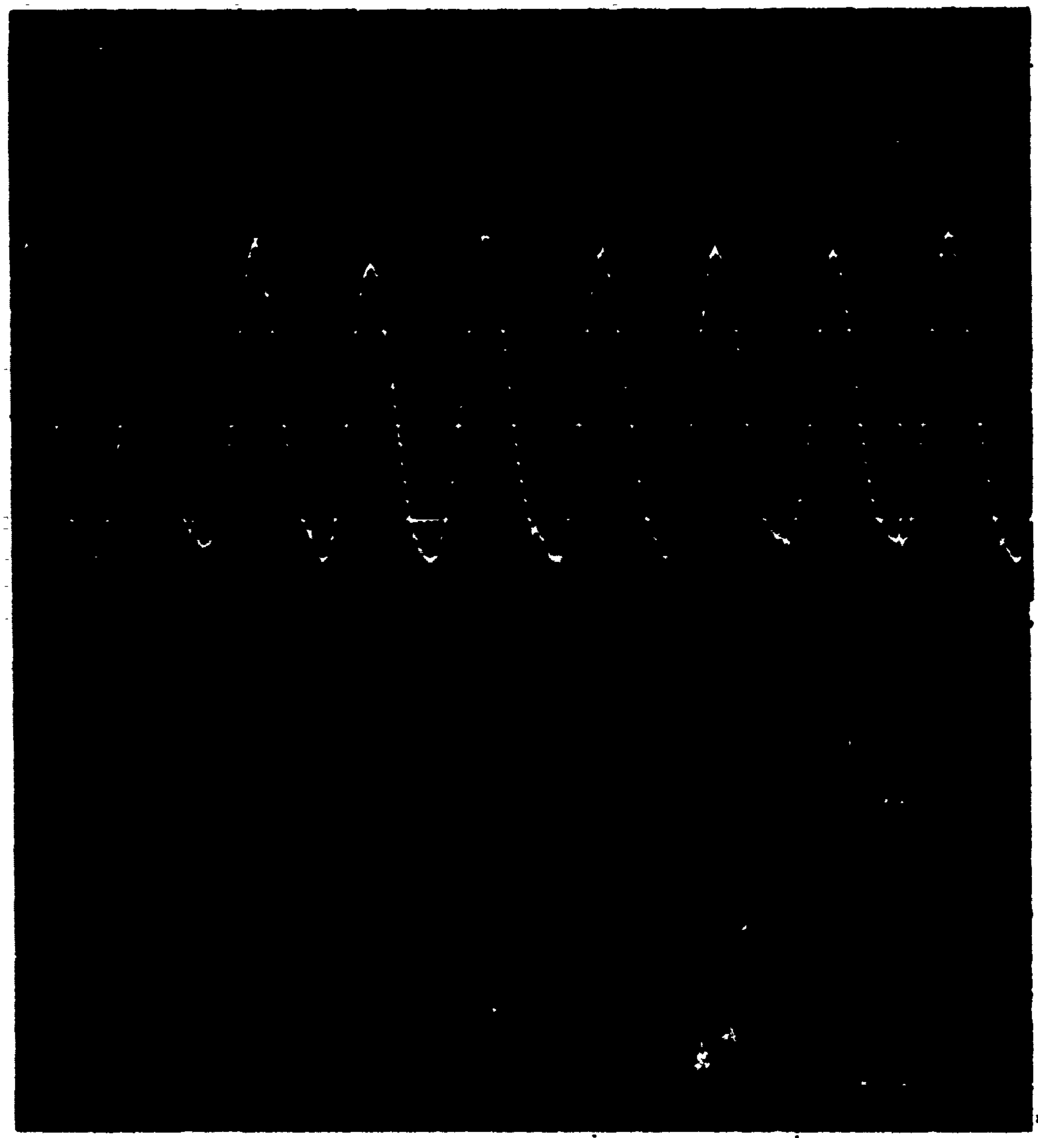


FIGURE 35

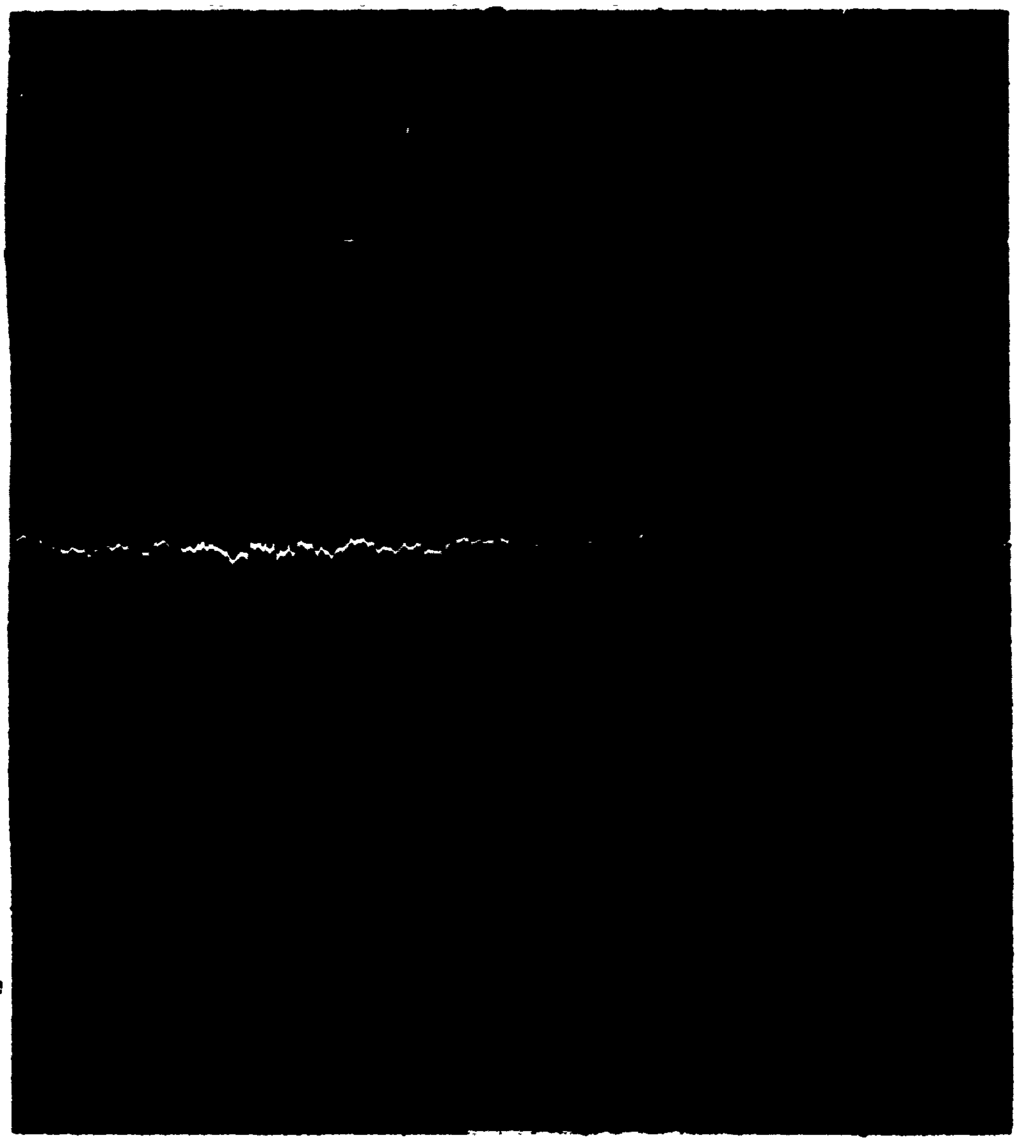


FIGURE 36

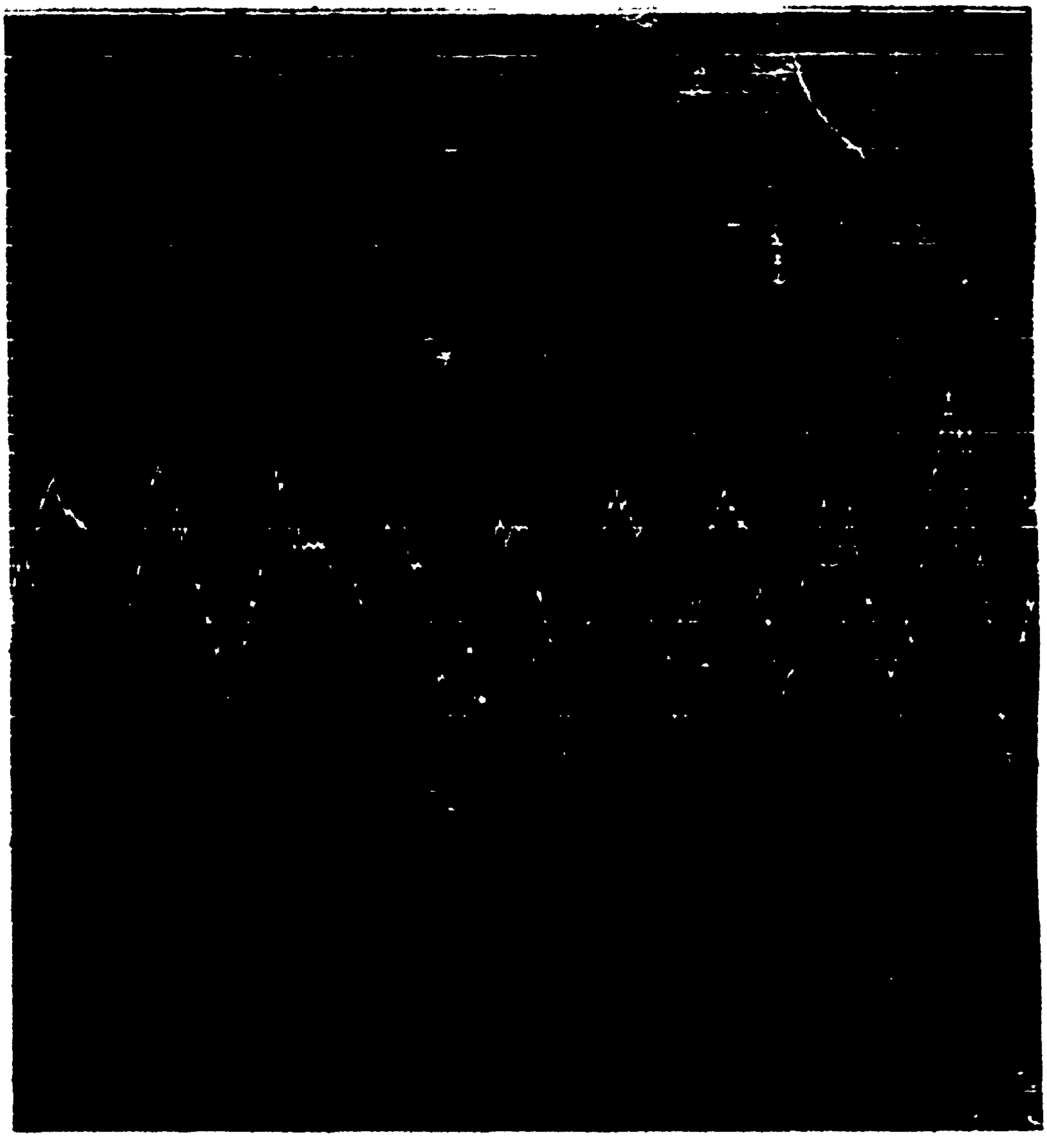


FIGURE 37

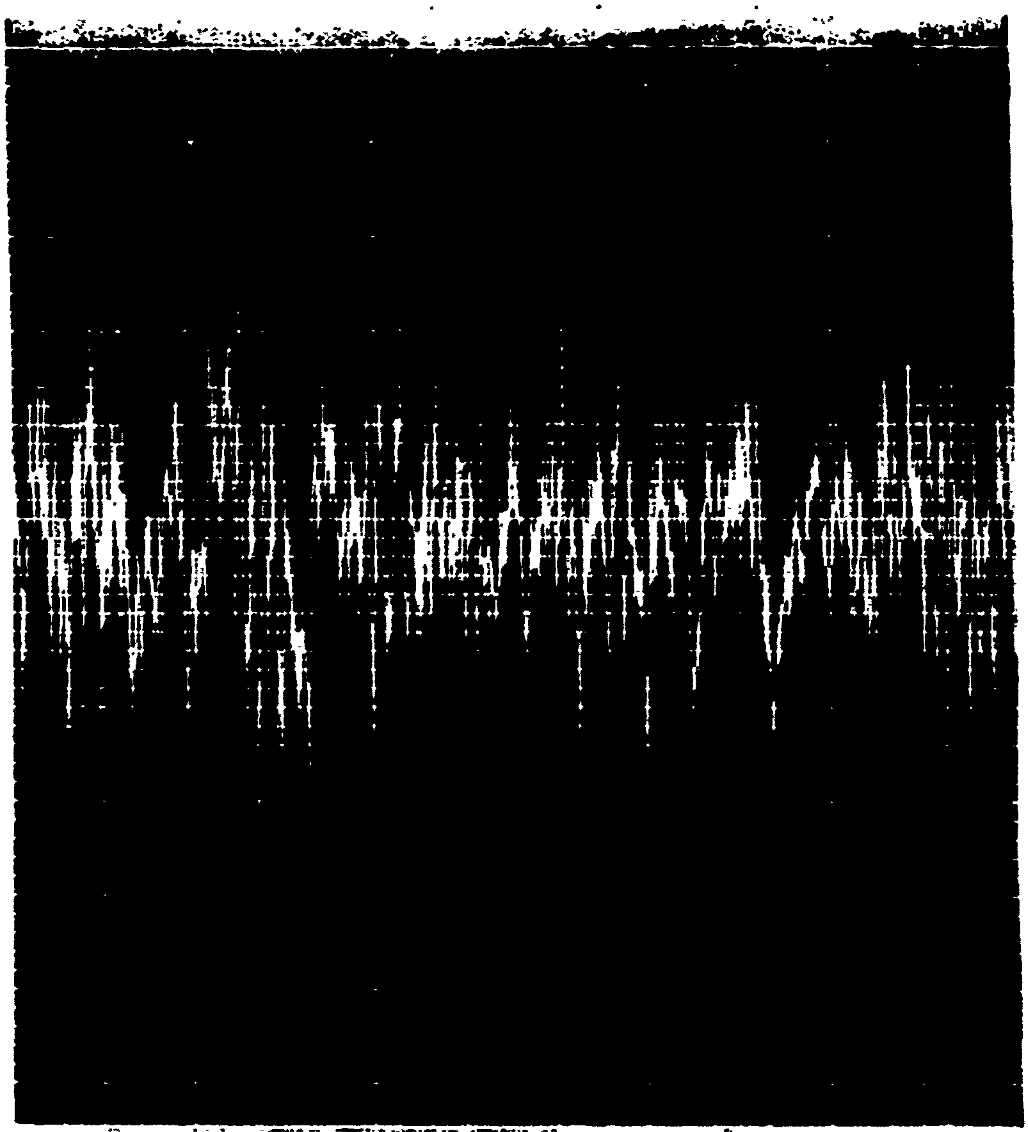


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FIGURE 38

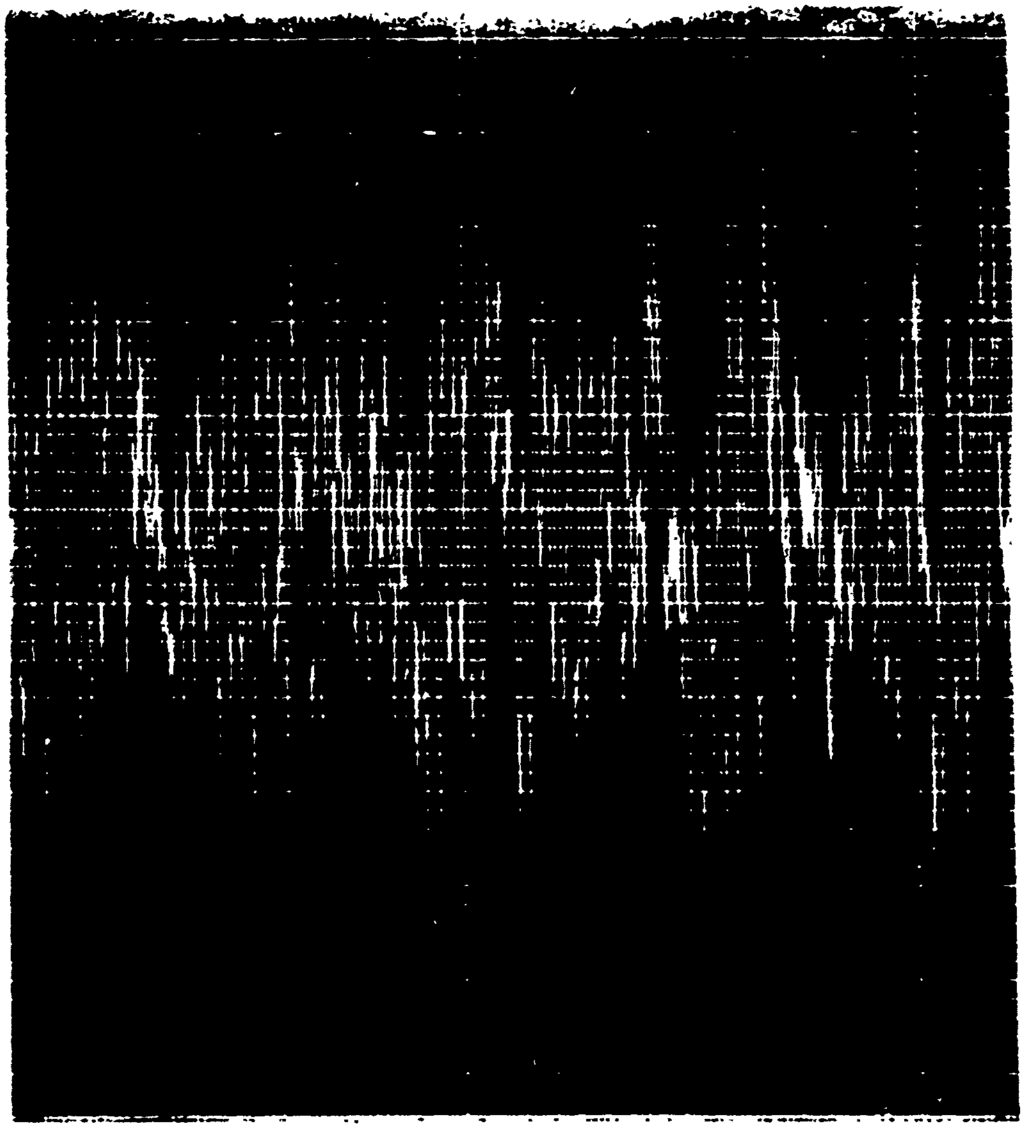

FIGURE 39

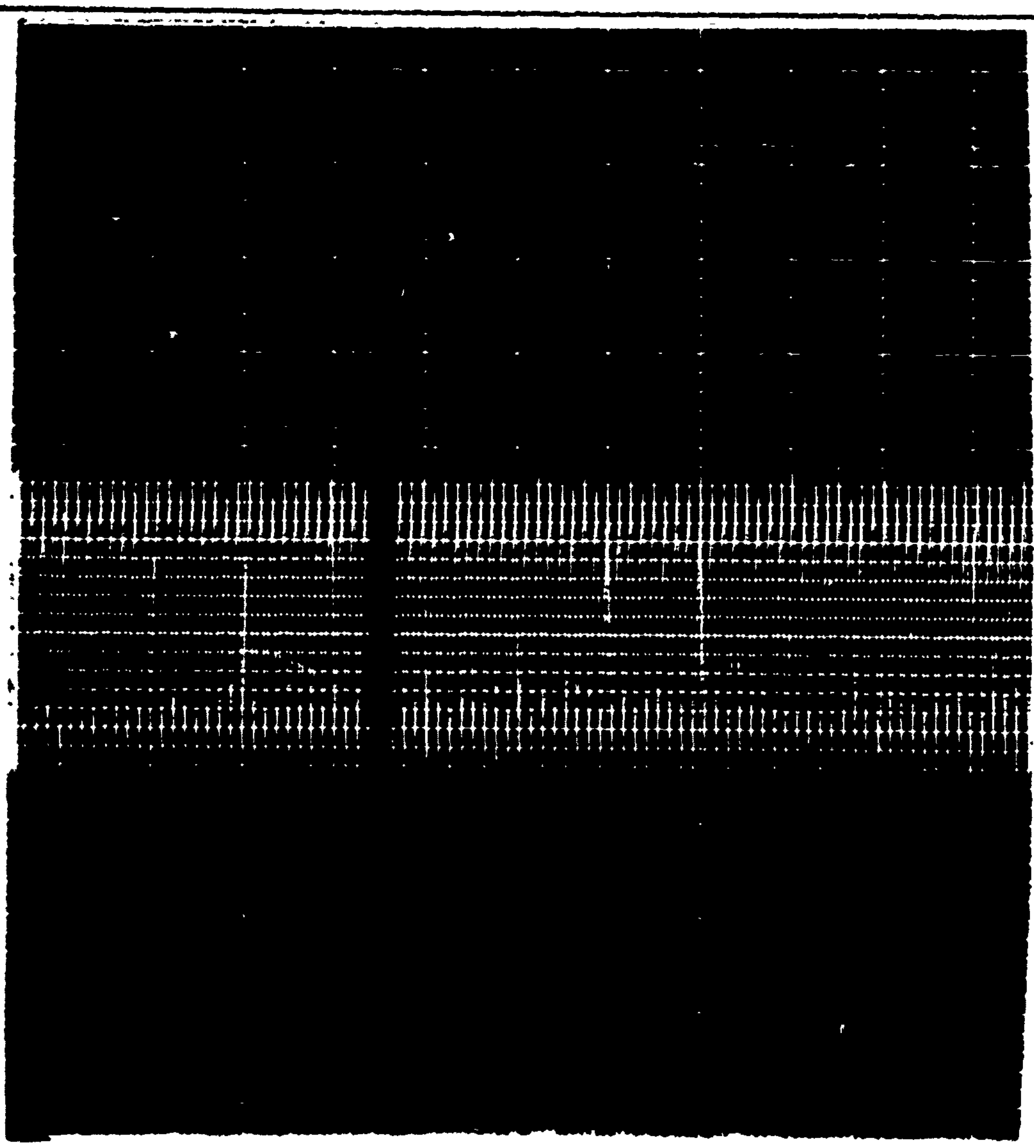

FIGURE 40

APPENDIX I - DESIGN, TEST, AND EVALUATION OF FIELD MILL PROTOTYPES

A - Prototype P1

It was decided that the first field mill prototype, P1, built during this investigation would be of the fixed conductor, or stator, type with a grounded rotating vane, or rotor, directly above it. Not knowing the magnitude of signal to expect, the rotor and stator were made very large, alternate quadrants of a 3 inch diameter circle. The stator vane and small d.c. motor, used to power the rotor vane, were mounted on a 3 inch diameter x $\frac{1}{4}$ inch thick piece of plexiglass. The mounting plate, stator, and rotor are shown in figure A1.

The only problem encountered in building this prototype was the need for an extremely high impedance amplifier in order that the condition $w^2C^2R^2 \gg 1$ be met in equation 12. During some previous attempts to measure electrostatic phenomenon by a d.c. method, a high input impedance (approximately 10^{14} ohms maximum) solid state Keithley electrometer model 610C was used. A frequency response check was made on the above instrument using a wave-tech signal generator and 502A Tektronic oscilloscope, figure A2.

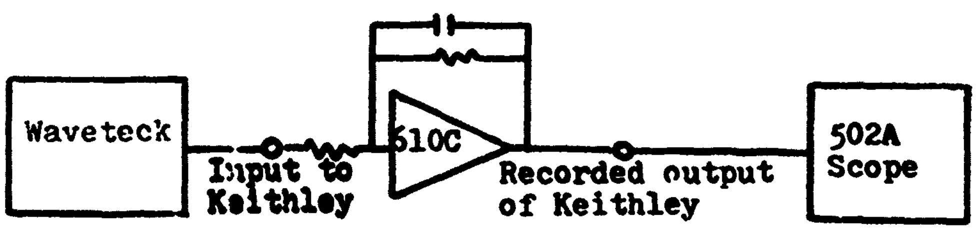

Figure A2

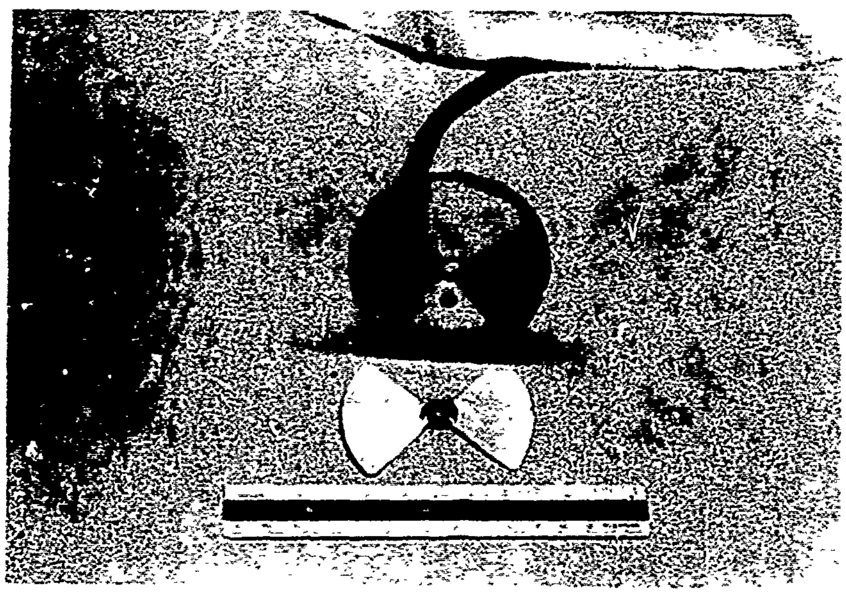

FIGURE A1-FIELD MILL PROTOTYPE P1

The signal generator was used to input a fixed amplitude sine-wave to the Keithley amplifier and the output of the Keithley was displayed on the scope. The frequency of the sine-wave was varied from 10 cps to approximately 3000 cps with several different gain settings on the Keithley. No distortion or reduction in amplitude of the sine-wave was observed. Since the maximum possible frequency of the alternating field mill signal was approximately 200 cps, the Keithley electrometer was used to amplify the alternating current induced on the stator plate.

Field mill P1 was now placed in the test capacitor as shown in figure A3. The stator plate was connected to the input of the Keithley by shielded cable. The recorder output of the Keithley was then connected to an oscilloscope. A potential of 2500 volts d.c. was applied to the test capacitor and figure A4 shows the field mill output signal wave form. A rough calibration of field mill P1 is presented in figure A5.

The investigator had expected the signal peak-to-peak voltage to be on the order of millivolts, but one can observe from figure A5 that the signal was on the order of volts. Hence, an immediate program to miniturize the field mill was started and no further tests were run with the above instrument.

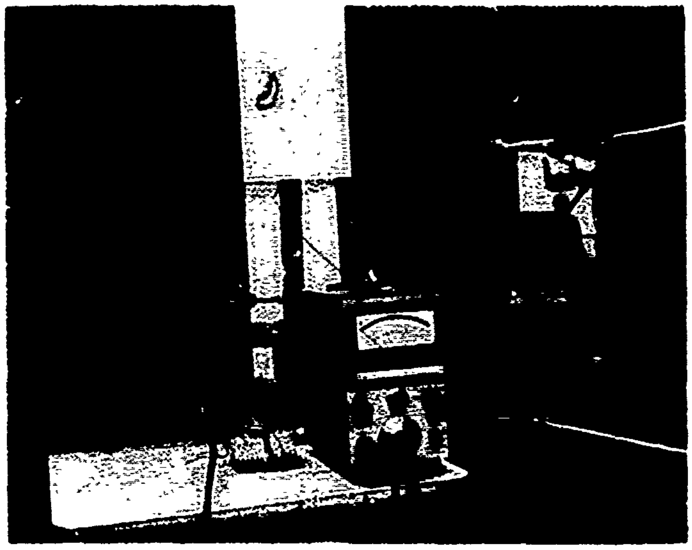

FIGURE A3—PI IN TEST CAPACITOR

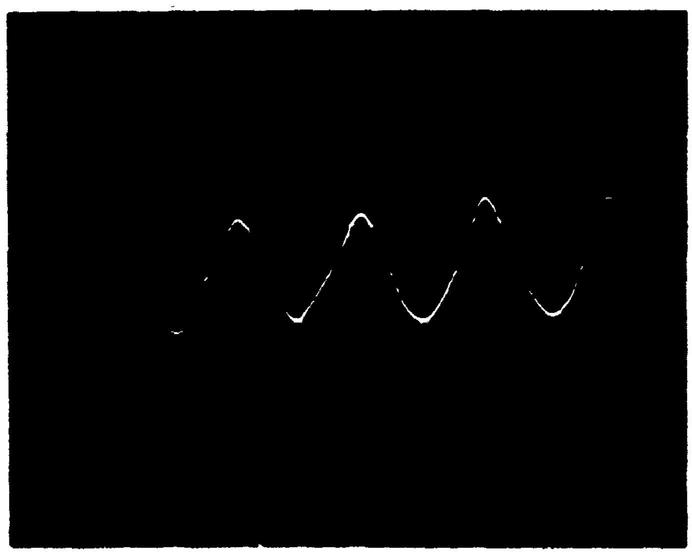

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FIGURE A4— PI SIGNAL WAVE FORM

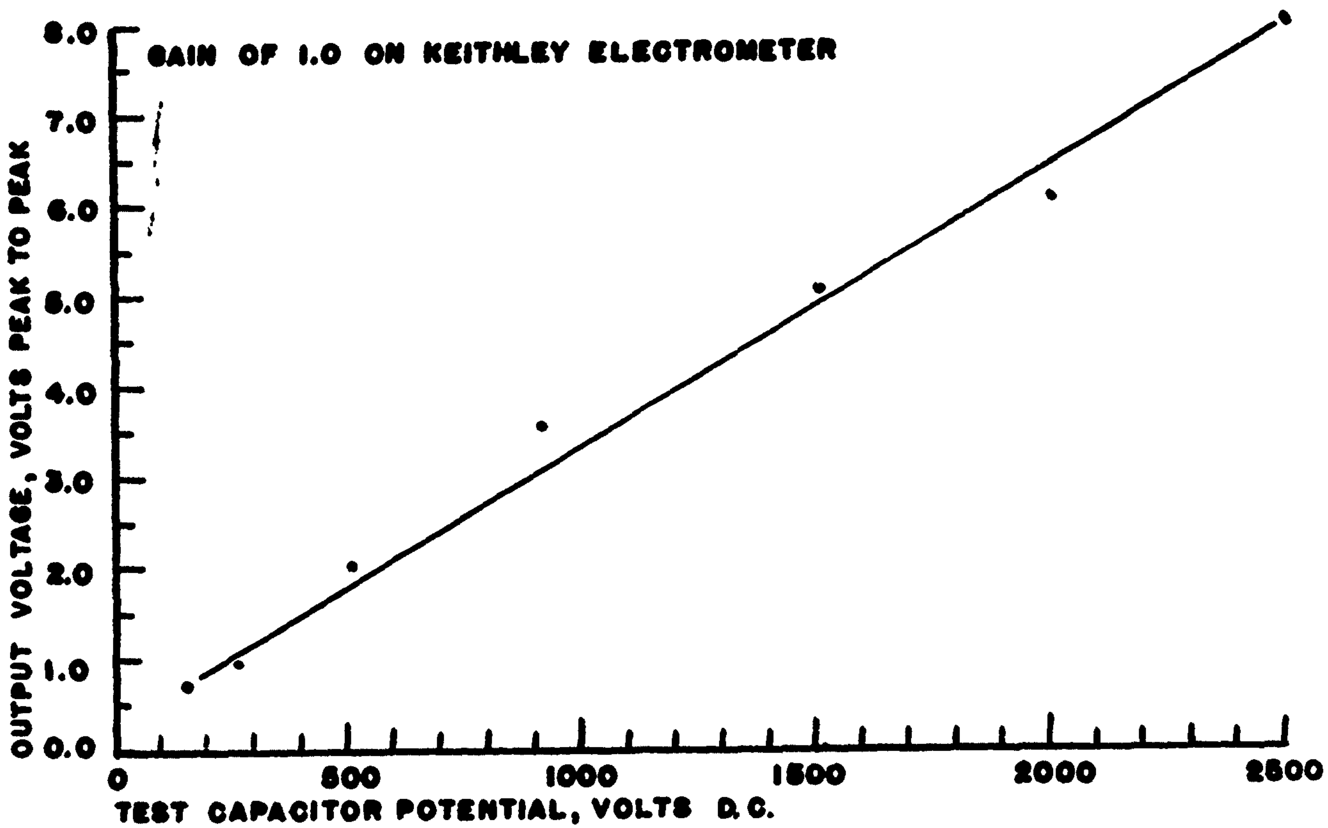


FIGURE A5 – PROTOTYPE NO.1 CALIBRATION CURVE

B - Prototype P2

The second prototype, P2 was identical to P1 except the rotor was made of alternate quadrants of a 1.5 inch circle, figure A6. P2 was again placed in the test capacitor and connected in the same manner as P1. The signal peak-to-peak voltage of the field mill was reduced but it was still in the low volts and high millivolt range. Hence, a smaller, completely new prototype, P3, was built.

C - Prototype P3

Field mill prototype P3 consisted of a stator and rotor made from alternate quadrants of a 3/4 inch circle. The stator and d.c. motor were mounted on a plexiglass plate 1 inch in diameter, figure A7.

P3 was again placed in the test capacitor, figure A8, and carefully calibrated, as shown in figure A9, from 0 volts per meter to 6500 volts per meter with a corresponding output peak-to-peak signal voltage of 1 millivolt to 49 millivolts. As one can observe, the experimental relationship between electric field strength and field mill output voltage was extremely linear. No statistical curve fitting procedures were deemed necessary.

During calibration of P3, it was noticed that the field mill output voltage would not go to zero when zero electric field was present. And in addition, this error voltage

FIGURE A6-FIELD MILL PROTOTYPE P2

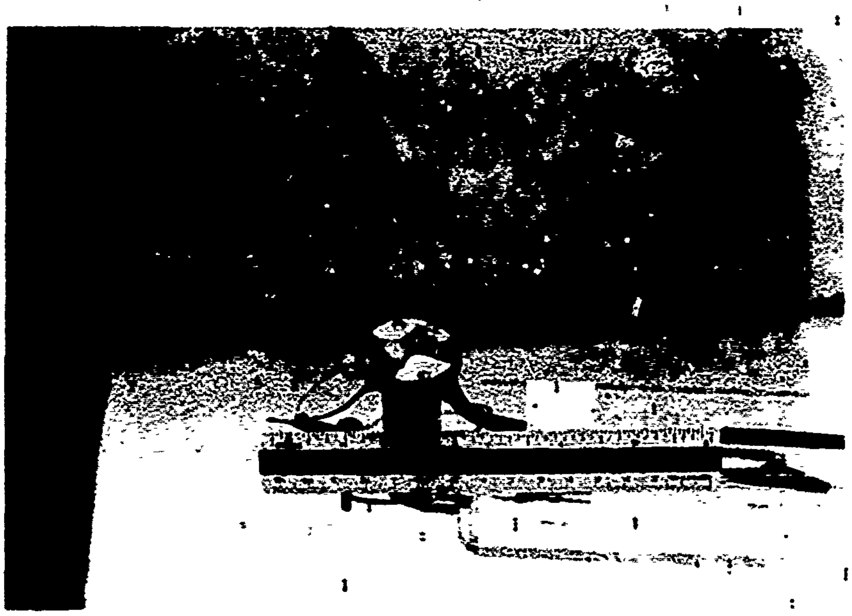


FIGURE A7- FIELD MILL PROTOTYPE P3 WITH MODIFIED STATOR

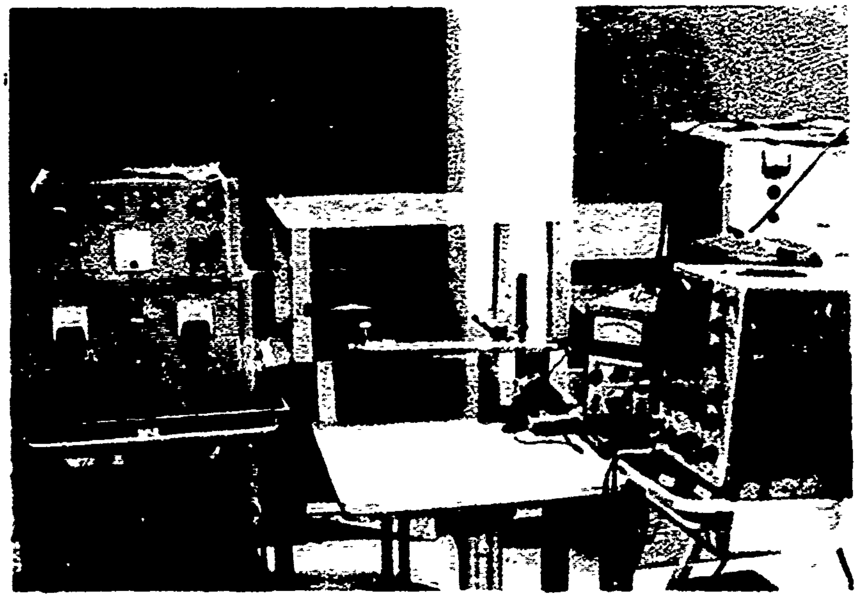


FIGURE A8- P3 IN TEST CAPACTOR

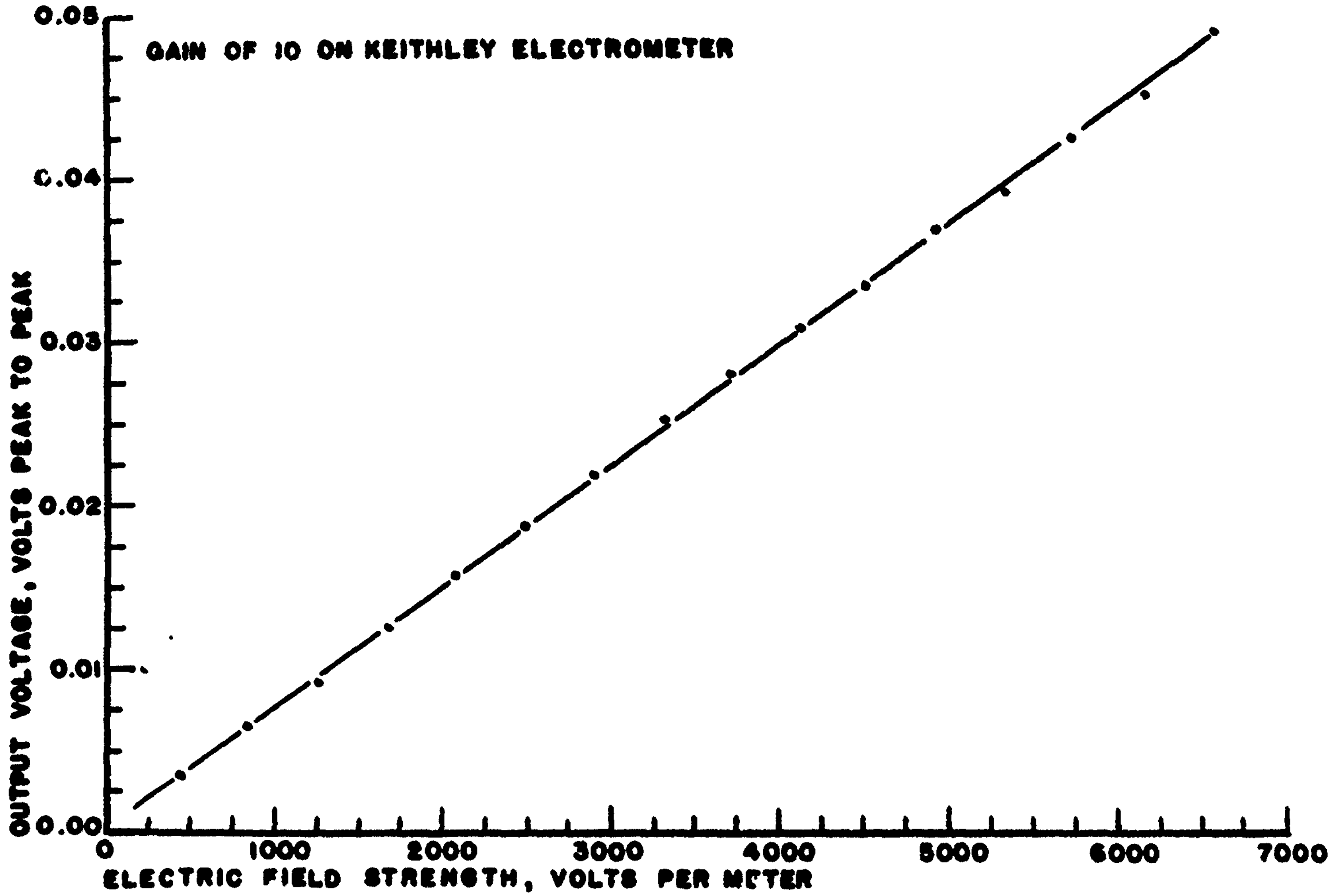


FIGURE A9 – FIELD MILL PROTOTYPE NO.3 CALIBRATION CURVE

was not constant but varied from several millivolts to a maximum of 100 mv for short periods of time. It was also noted that, if a grounded probe touched the plexiglass mounting plate in zero field, the error voltage would change. Therefore, it was concluded that bound static charge was being built up on the plexiglass plate. To correct this the alternate quadrant stator was modified to a full circle with two alternate quadrants acting as sensor and two alternate quadrants electrically isolated and grounded, as shown in figure A7 and figure A10.

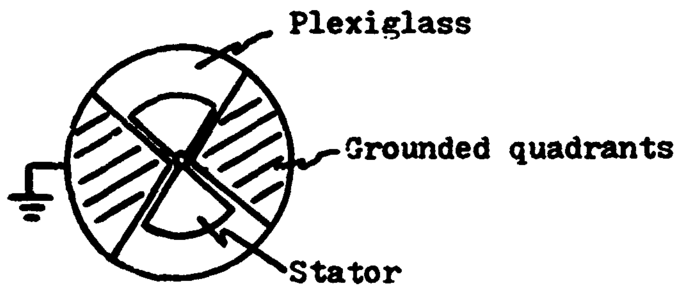


Figure A10

The zero field output voltage was again checked and this time it remained constant at approximately 4 millivolts.

It was also noted, during testing of field mill P3, that a movement of the shielded cable connecting the stator to the Keithley amplifier caused the field mill signal to move up and down on the oscilloscope display. It was hypothesized that movement of the cable caused small d.c. currents to be produced which displaced the mean d.c. voltage

around which the field mill signal was modulated. It was feared that when the field mill was placed in the wind tunnel, the output signal would be destroyed by the above. Therefore, it was decided to place the field mill in the wind tunnel to determine the degree of seriousness of the above, and to look for any unforeseen problems.

D - Prototype P3 - Tunnel Tests

Field mill P3 was orientated in the wind tunnel as shown in figure All.

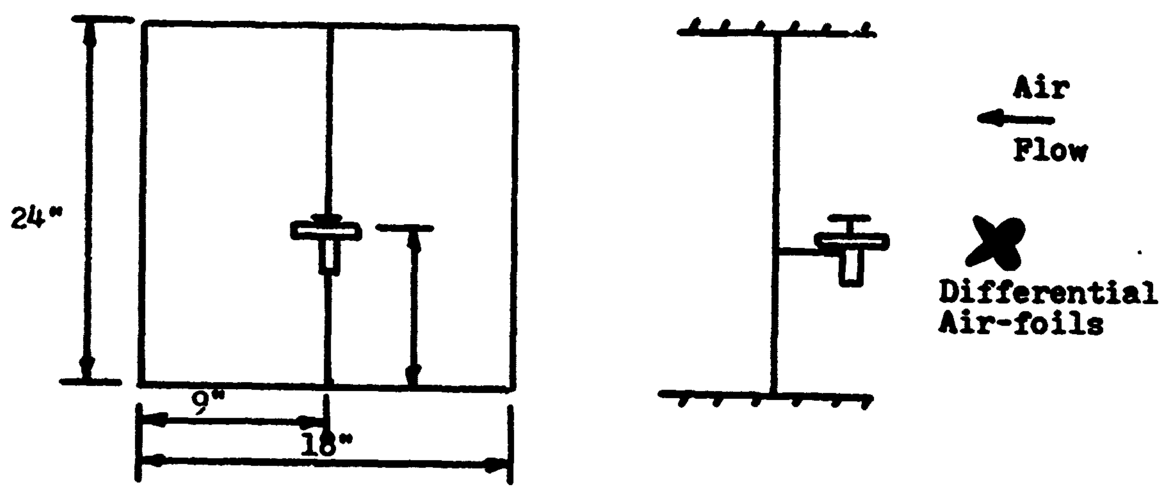


Figure All

It was placed 6 inches behind a differential air foil set at $\pm 7^{\circ}$ angle of attack with an air speed of 140 fps. The height, h, of the stator was varied from 25 inches to 16 inches with corresponding electric field reading being taken at each point under the following conditions:

(1) tunnel air flow only.

(2) tunnel air flow plus nozzle (dust feeding system) air flow.

(3) tunnel air flow seeded with a suspension of dust particles.

The electric field at the first data point, h = 2.5 inches, was approximately 500 V/m under conditions 1 and 2. When dust was added to the airstream, condition 3, the electric field increased to approximately 6000 V/m and the output signal was a perfect sine-wave with zero noise distortion. Hence, the field mill seemed to be performing well and the cable movement caused little problem. However, when the dust and tunnel were shut down, the field mill still indicated an electric field strength of 6000 V/m. The investigator then opened up the wind tunnel and wiped his hand over the remaining exposed area of the plexiglass mounting plate. This reduced the indicated electric field to 200 V/m. Hence, the old problem of bound charge build-up on the plexiglass plate was reappearing but to a much more serious degree. This was due to the triboelectric charging (friction charging) of the dust particles on the plexiglass.

In spite of the above problem the tunnel test was continued with data taken at several h values (the plexiglass plate was discharged between each data point). A graph of the electric field gradient obtained in this manner is presented in figure A12. However, no conclusions can be drawn from these tests as long as the electric field, due to the dust particles, is distorted by the bound charge on the plexiglass.

Therefore, the entire plexiglass mounting plate was coated with conducting silver paint and grounded, and the stator was electrically insulated from the conducting silver, see figure A13.

With these modifications made the field mill was again placed in the wind tunnel in the same orientation as before with h = 5 inches. Again dust was injected into the airstream. This time the output signal from the field mill was not steady in amplitude but was varying, as would be expected. The tunnel and dust was shut down, but the output signal of the field mill persisted. It indicated an electric field strength of approximately 1000 V/m. The investigator again opened up the tunnel and wiped his hand over the silver-coated plexiglass plate; the signal persisted. But, the signal would go to zero if one's hand was placed directly above the field mill, which would indicate that a field of this strength was actually present in the tunnel and was being shielded from the stator by one's hand. The only

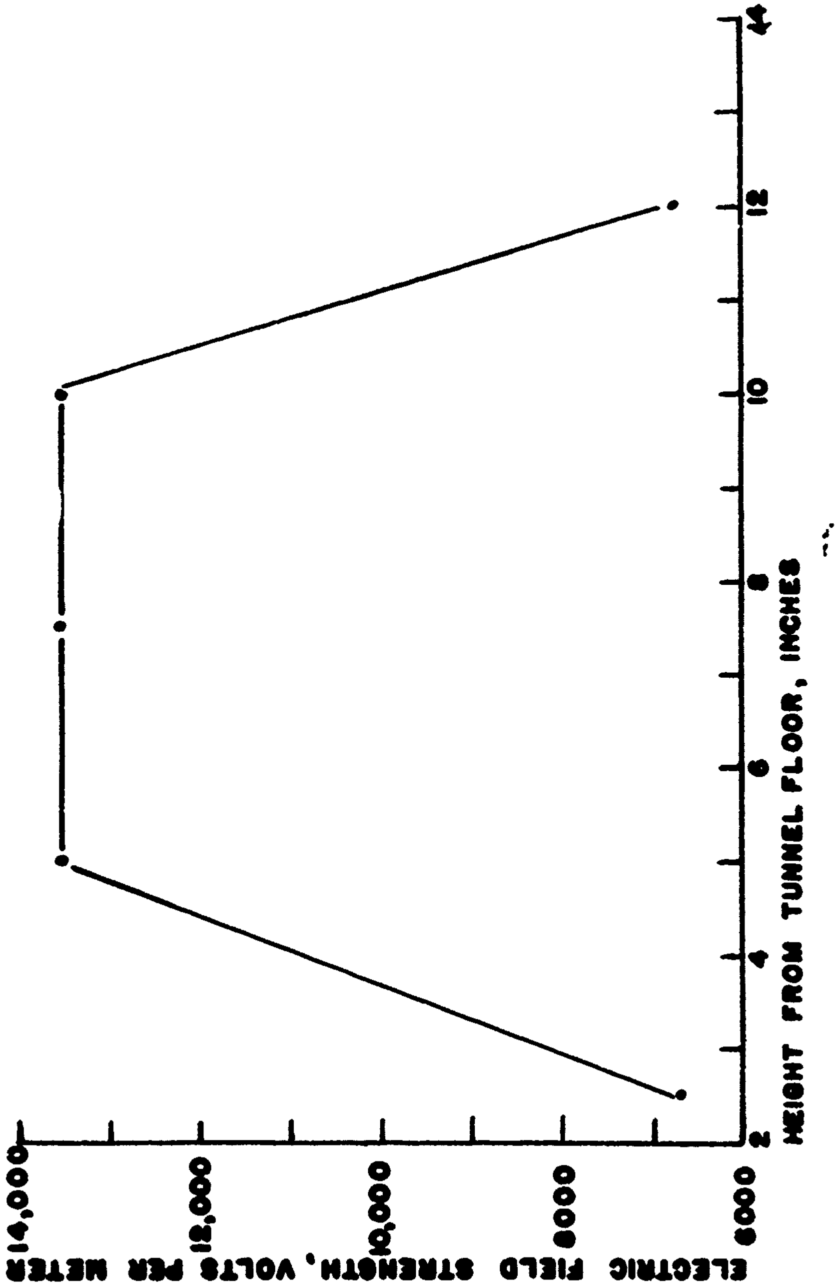


FIGURE A12 - ELECTRIC FIELD GRADIENT

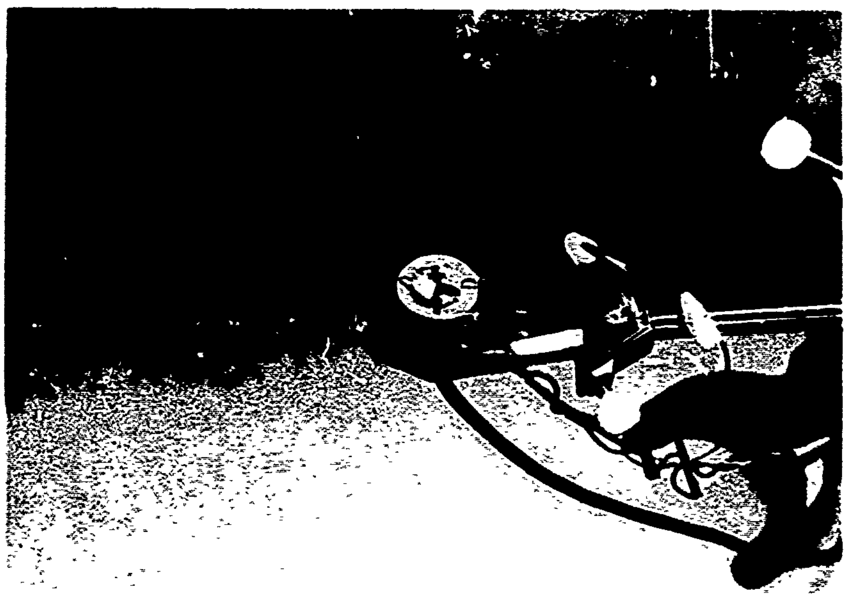


FIGURE A13 - P3 COATED WITH CONDUCTING PAINT

surface above the field mill was a window in the wind tunnel, and it so happens that this window was made of plexiglass. The field mill stator was now orientated approximately 1 inch away from the window. An electric field strength of approximately 68,000 V/m was indicated. This corresponds to a potential of approximately 1700 volts on the window. The varnished wooden walls of the tunnel were also checked for static charge built-up and none was found.

Again, the field distortion caused by these windows would make any electric field gradient measurements invalid. Therefore, the windows were covered with aluminum foil.

Since the dust particles were clogging the exposed d.c. motor of the field mill, all further planned tests were discontinued until a completely sealed field mill could be obtained (this model is discussed extensively in the main body of this investigation). However, many interesting conclusions, which are listed below, have been obtained from the above tests.

(1) The vibration of the shielded cable was not as serious a problem as predicted.

(2) The charging of the plexiglass mounting plate proved to be a serious source of error but could be eliminated by design changes.

(3) The performance evaluation of the field mill in obtaining electric field gradients was

surface above the field mill was a window in the wind tunnel, and it so happens that this window was made of plexiglass. The field mill stator was now orientated approximately 1 inch away from the window. An electric field strength of approximately 68,000 V/m was indicated. This corresponds to a potential of approximately 1700 volts on the window. The varnished wooden walls of the tunnel were also checked for static charge built-up and none was found.

Again, the field distortion caused by these windows would make any electric field gradient measurements invalid. Therefore, the windows were covered with aluminum foil.

Since the dust particles were clogging the exposed d.c. motor of the field mill, all further planned tests were discontinued until a completely sealed field mill could be obtained (this model is discussed extensively in the main body of this investigation). However, many interesting conclusions, which are listed below, have been obtained from the above tests.

(1) The vibration of the shielded cable was not as serious a problem as predicted.

(2) The charging of the plexiglass mounting plate proved to be a serious source of error but could be eliminated by design changes.

(3) The performance evaluation of the field mill in obtaining electric field gradients was

limited by the distortion caused by the bound charge on the plexiglass mounting plate of the field mill and the plexiglass windows in the wind tunnel.

However, the field mill proved that it was valuable as a diagnostic instrument for determining the effects of the wind tunnel walls on the electric field.

(4) The observation was made that a notch or band-pass filter might be needed when the field distortion effects were eliminated.

E - Test to Evaluate the Asymmetric Wave Form Method of Polarity Determination.

A simple method for determining the polarity of an unknown electric field, using a field mill, was introducing an asymmetry in the output wave form (ref. 12). The above could be accomplished by shaping the stator and rotor vanes as shown in figure A14-A. Now the peak-to-peak voltage of the field mill was given by equation 12 as

$$V = \frac{\epsilon A}{2C} E$$

where A was the maximum exposed, or screened, area. When the rotor vane is in the position shown in A14-B, the value of A is A_1. When the rotor is the position shown in A 14-C, the value of A is A_2. But A_1 is less than A_2. Therefore, V_1 will be less than V_2 and the wave form presented in figure A14-D will result. When the polarity of the electric field changes, the wave form will change to that shown in figure A14-E.

Thus, if the field mill signal was displayed on an oscilloscope and the position of the asymmetrical wave form noted for a certain polarity, the polarity of an unknown electric field would also be known by observing the oscilloscope display. Figure A15 presents pictures of oscilloscope displays demonstrating the foregoing principles.

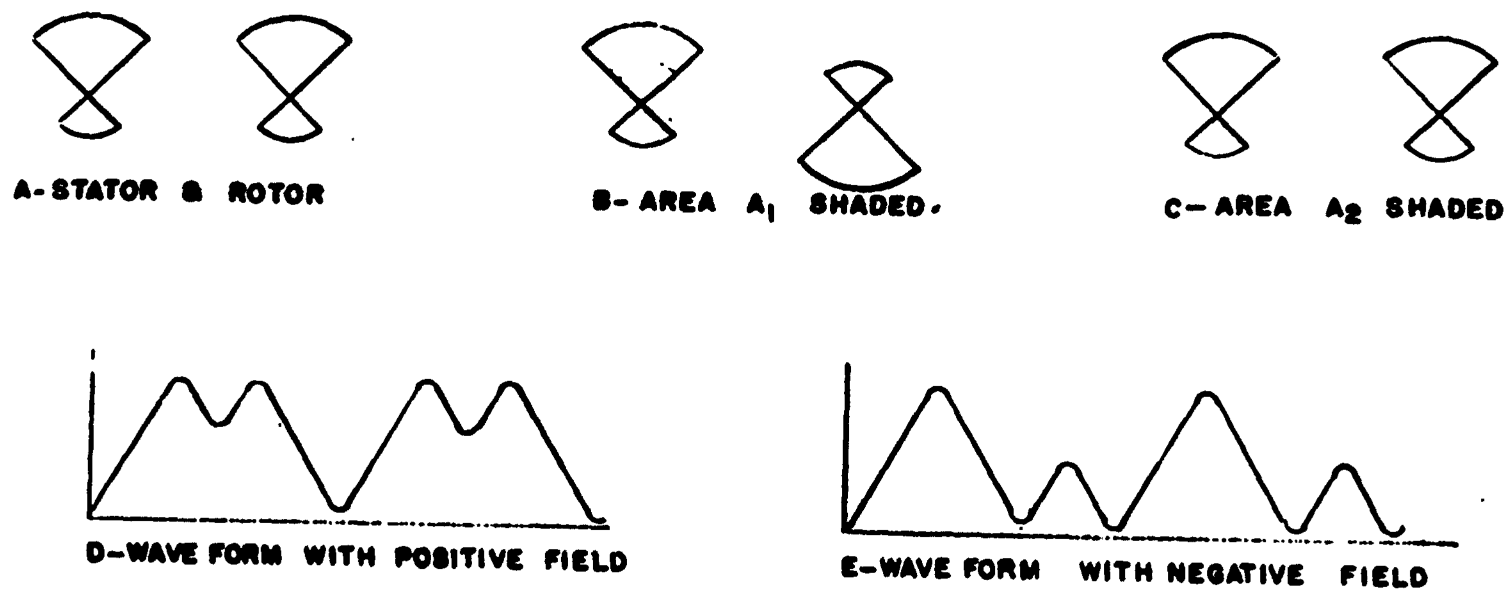
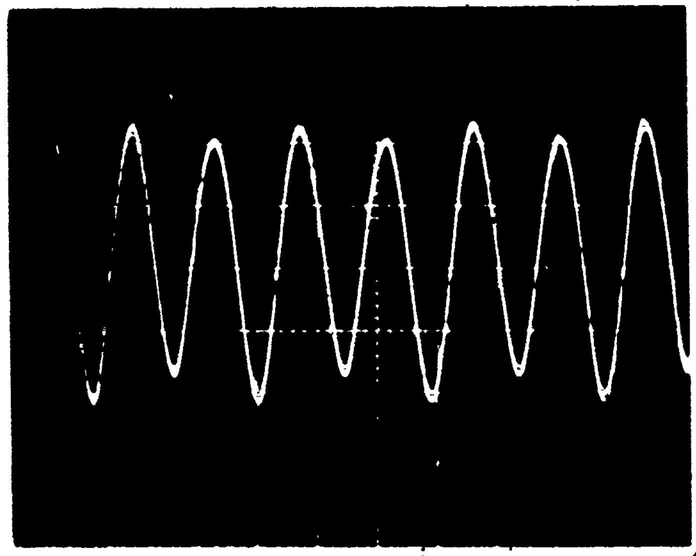


FIGURE 14A—ASYMETRIC WAVE FORM METHOD OF POLARITY DETERMINATION



A-POSITIVE ELECTRIC FIELD

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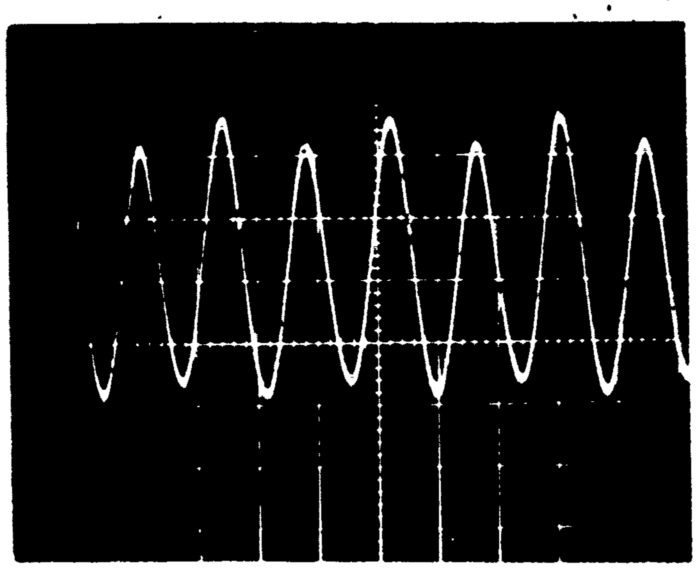

B-NEGATIVE ELECTRIC FIELD

FIGURE A15—ASYMMETRIC WAVE FORMS

The only problem with using an asymmetric wave form for determining polarity was the inability to distinguish the above wave form in a varying electric field. Hence no further study was made of this technique.